



'Geographical Information Science & Systems' (UNIGIS MSc)
International Institute for Geoinformation (Z_GIS)
of the Paris Lodron University
Salzburg

Spatial Agent-Based Modelling applied to Irrigation Agriculture Dynamics in the Choapa-Valley, Chile

by

Dipl. Geogr. Günther Grill

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Supervisor:

Ao. Univ. Prof. Dr. Josef Strobl

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Abstract

The objective of this work is to add to the research of complexity in environmental modelling by exploring the Agent-Based Modelling approach applied to the field of land use change dynamics. The author built a prototype of an Agent-Based Model, the 'Choapa' Model simulating irrigation agriculture dynamics in an arid environment in Northern Chile. The model is a spatially explicit model, loosely coupled to Geographic Information Systems (GIS).

Agricultural activity is simulated based on micro-level multi criteria decision making, which is carried out by complex agents with adaptive capabilities. The decision model is designed out of components from declarative and imperative decision methods. For the declarative part, 'objective functions' and heuristics are used to decide if and where to plant, whereas for the imperative side, a 'learning' mechanism is introduced to simulate migration as well as technology adaptation and diffusion.

Another facet of the individual agents decision model is a spatial decision making component, adapted from the classical 'spatial decision support system approach' using the weighted sum as an aggregation rule.

Technically, the model is an object-oriented model coded in Java, making extensive use of the Repast 3 Java libraries. It consists of five interacting classes in which the agents are embedded and which holds environmental attributes for decision making.

The explorative and empirical capabilities are demonstrated within an exemplary assessment of modelling long-term relative sustainability of agriculture activity as a result of climate variability and climate change. Two scenarios were compared and the spatial and quantitative effects on agriculture activity in the study area are presented and discussed.

Spatially disaggregated maps of agricultural core zones based on simulated water availability and climate variability are presented.

Keywords:

Spatial Agent-Based Modelling, Micro Level Decision Making, Irrigation Agriculture, Climate Change, Chile

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1 Introduction

A special interest in environmental research is related to climate change and the possible long-term effects on the physical environment and on society. However, land use change is the result of complex interactions between social actors, and between social actors and their environment. Integrating social interaction based on behaviour theory and individual decision making in an environmental model framework is a demanding task. In addition to that, there is a high level of uncertainty involved, due to the difficulty to predict the long-term effects of climate change on environmental systems.

A novel and promising approach in integrated environmental modelling to tackle these complex tasks is Agent-Based Simulation (ABS). Agent-Based Simulation is able to integrate environmental dynamics and social interaction between individuals into a common framework. The strength of Agent-Based Modelling is to simulate and explore the macro structures of a system as a result of micro-level decision making of actors and their social interactions.

The capabilities of ABS are best explored in an applied case. In the context of this work, it was a case study in an (semi-) arid environment in the 4th region in Northern Chile, the Choapa Valley. This region seemed best suited for the study for the following reasons: Firstly, there are strong indications for recent climate change, e.g. empirical data of different climate stations indicate that precipitation dropped up to 30 percent in the last three decades. Secondly, the climate variability is relatively high and a negative impact of the El-Nino Southern Oscillation (ENSO) phenomena was identified. Thirdly, human economic activity and security in the Coquimbo region is based on irrigation agriculture, and is thus strongly related to climate and its variability.

For the mentioned reasons, it is necessary to explore the effects of climate variability and change on the socio-economic system in order to mitigate and avoid negative effects to the region.

1.1 Research Approach

1.1.1 Objectives

Build an Agent-Based Modelling framework

The main objective of this work is to develop a spatially disaggregated modelling framework to explore the external and internal factors that influence the spatial dynamics of irrigation agriculture in the face of the high short-term climate variability and the long-term climate change in the Choapa Valley in Chile.

Design the model as exploratory computational laboratory.

Ideally the framework will be flexible enough to act as a computer laboratory to explore the dynamics from different perspectives and at various levels. The main parameters that determine the spatial dynamics of irrigation agriculture should be identified, and be accessible to be altered in order to explore the effects.

Find emergent properties

To find and explore macrostructures that emerge from micro behaviour of the agents can add to deeper understanding of the system's functioning and dynamics. These 'emergent' properties of a system are difficult to be explained by the behaviour or by the properties of a single individual or element in isolation.

Explore suitability of spatial Agent-Based Modelling

Explore critically the suitability and applicability of Agent-Based Simulation in a spatially based approach based on results and experiences of the case study. The role of GIS in the context of Agent-Based Modelling will be discussed.

1.1.2 Research Questions

- What are the main environmental, economic and social factors that influence the spatial structure and dynamics of irrigation agriculture in the face of high short-term climate variability and long-term climate change?

- How can these factors be successfully integrated into a flexible, spatially disaggregated simulation model?
- How is a change in short-term rainfall patterns and long-term climate change affecting land-use patterns in the study area?
- Are there emergent properties, which improve the understanding of the system under study

1.2 Methodology and Justification

1.2.1 Arguments for Agent-Based Modelling

Account for different data sources and knowledge types

Environmental problems in the face of climate change are often referred to as 'wicked' or 'messy' problems with a high degree of complexity and uncertainty involved on different levels (Pahl-Wostl 2005, Vennix 1999). Dealing with these kinds of problems is difficult, especially in developing countries, where consistent and quality aggregate data hardly exists. The research methodology must correspond to this and be flexible enough to pragmatically incorporate different types of knowledge (classifications, rules, relations, cause and effect chains, structures, semantics) based on expert knowledge, personal observation, or experimental surveys.

Account for complexity and integration

The Agent-Based Modelling approach fulfils these requirements. On the one hand an Agent-Based Model requires disaggregated quality data, especially if the model fulfils the role of an empirical prediction model. On the other hand, as a kind of explorative model, the Agent-Based approach is capable of integrating a wide range of data of different scales and knowledge types into the model. One of its advantages is its object-oriented design. This makes it relatively easy for the modeller to incorporate higher-level concepts. The coder can model the problem

based on descriptions and terms of the problem domain, rather than in computer terms; therefore he can use higher abstraction levels.

An ABM can be more realistic than traditional models, e.g. system dynamics, because an ABM can link together the advantages of environmental and social models into a common framework. The ABM framework permits to incorporate the concept of adaptive social interaction between agents. Interaction could be based on imitation of the behaviour of his neighbour, for example of those which are similar to him or those which are perceived as successful. This kind of neighbourhood requires a spatially explicit environment.

Account for individual decision making

Apart from social interaction, an agent has another component that constitutes his ability to decide on his behaviour at any point in time. The underlying decision making models of an Agent-Based Model can be very different, e.g. it could consist of a more objective optimization or profit oriented model used in economics. Decision models can also consist of a set of 'if-then' rules and decision trees. With the Agent-Based approach, it is possible to account for individual decision making in a flexible manner adding more realism to the model.

Account for spatial complexity

Many modelling approaches are based on system dynamics in a spatially non-explicit environment. However, it is often underestimated that spatial patterns and constraints deeply influence the system's behaviour, and therefore the simulation outcome. This is especially true for Land Use Change dynamics in the agriculture domain. A pronounced spatial dynamic is the case in many regions with intense agriculture activity, due to the spatially varying factors that influence agriculture activity (i.e. slope, soil fertility). With the above mentioned concept it is possible to make individual decisions based on spatial attributes of the agents' environment. The decision of planting on a specific space or cell will not be globally determined, but depends on each agent's preferences and the attributes of his environment. For example, depending on the different technology level of a farmer, the farmer may or may not decide to plant on steeper slopes.

1.2.2 Research Model

Figure 1-1 gives an overview of the research model. The research started with a preparation phase in which the problem was framed and explored in its real world setting (see Section 4.1). In the case of this work, it was a region in the northern part of Chile, where the author reviewed literature, collected spatial data, carried out personal interviews, and learned from local experts. Hence, a knowledge base was created step by step, that served as a basis for further modelling (see Section 4.3).

In the modelling phase, cause and effect relationships were expressed; conceptual models designed and discussed, and basic system dynamics were sketched (see Section 4.5.1.2). The coding of the model was started after the first conceptual models were outlined. The coding of the prototype took up about 4 weeks of full time coding; debugging and calibration (see Section 4.5).

With the prototype, a set of scenarios were expressed (see Section 4.5.6) and simulation runs were carried out (see Section 4.6.1). The results were analysed based on interpretation of output graphs and with local spatial analysis methods. Based on the results, hypotheses were formulated and verified by comparison to real world spatial data and discussion with local experts (see Section 4.7 and Chapter 5).

Based on the simulation results and its interpretation, the source code of the model was modified and hypotheses were reformulated, so guaranteeing an 'adaptive' research methodology.

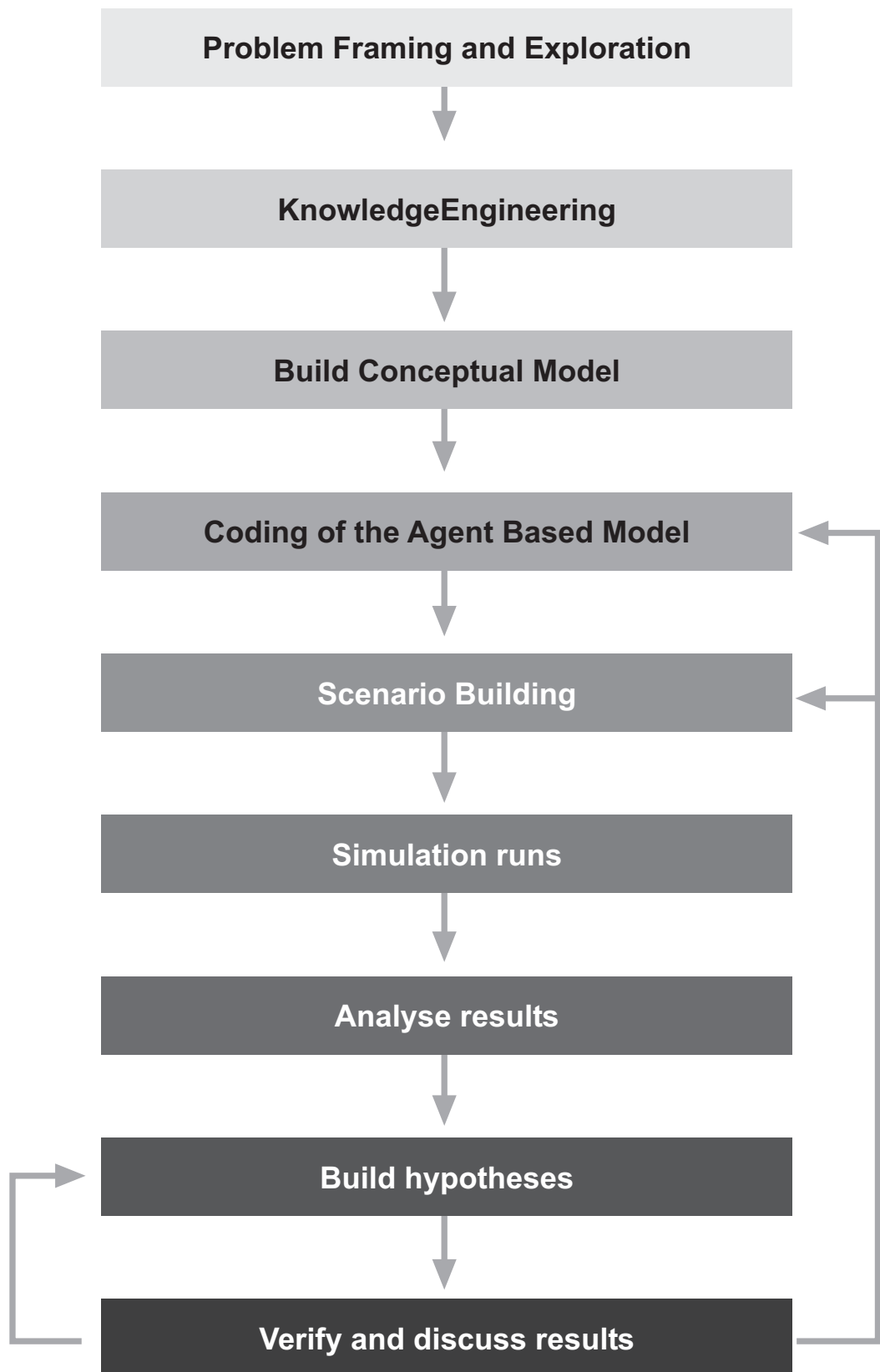


Figure 1-1: Research model

2 Agent-Based Modelling

The following chapter gives an overview of the Agent-Based Modelling (ABM) framework. The overview starts by defining the position of ABM within the science theory. After this, a short review of the roots of ABM is given and the term ‘agency’ is defined briefly. Afterwards the possible roles of ABM are discussed. The presentation of the different concepts and components of ABM is followed by a typology. The chapter ends with an analysis of ABM from the technology viewpoint, and different simulation builders and tools are presented.

2.1 A “Third Way” of Science

Agent-based simulation is a new approach in environmental modelling (**Parker et al. 2001**). There is ongoing discussion about what ‘kind’ of science it represents. Some authors argue that simulation in general and ABM in particular, is neither purely deductive nor purely inductive science, but a “third way of science” (**Axelrod & Tesfatsion 2005**). Figure 2-1 shows the difference in comparison to traditional science. In many ABMs, a set of assumptions regarding agent behaviour and interaction is the starting point. After different simulation runs, an output set of simulated data is produced, which will be analyzed with inductive techniques, because the simulated results cannot be proved with mathematical techniques or logic. However, unlike classical inductive techniques, the analysis is not based on real-world measured data, but on the simulated set (**Parker et al. 2001**, **Axelrod & Tesfatsion 2005**).

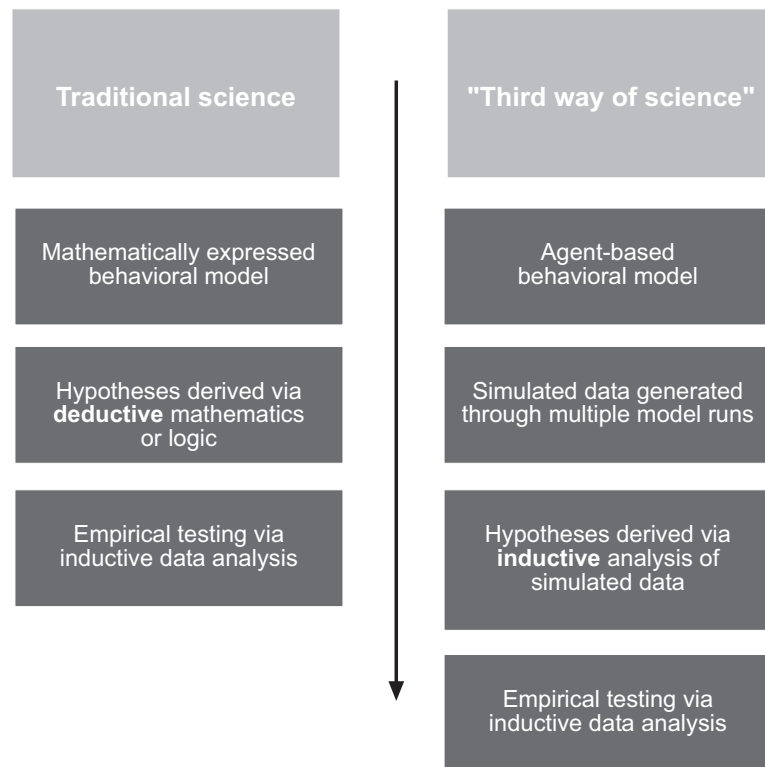


Figure 2-1: Differences between “traditional science” and Agent-Based Modelling as a “third way of doing science” (after **Parker 2005**).

2.2 Terminology

In the following sections, the terms Agent-Based Modelling (ABM) and Multi Agent Simulation (MAS) are used to summarize a semantic “morass” (**Hare & Deadman 2004**) of terms identified in literature. The most widely used terms include Agent-Based Modelling, agent-based simulation modelling, multi-agent simulation, multi-agent-based simulation, agent-based social simulation and individual-based configuration modelling. The author of this work does not argue that these concepts mean the same, but there is a need to “disentangle” the terminology “to reduce these terms to a smaller set of less ambiguous, more distinct terms” (**Hare & Deadman 2004**, p. 26). **Hare & Deadman 2004** identified the differences of the concepts mentioned above in the type and complexity of (social) interaction, ranging from interaction based on simple rules to interaction spawn from “deliberative social cognition”.

2.2.1 The Roots of ABM

There are three main “roots” that above-mentioned differences derive from. The first root is Individual Based Modelling (IBM), with an emphasis on ecology. In IBM disaggregated populations of organisms act as agents. (Grimm & Railsbach 2005). Secondly, there is the field of Artificial Intelligence, trying to simulate ‘life-like’ behaviour of macro elements by the more or less simple interaction of its micro entities (Langton 1988). Thirdly, there is the field of Distributed Artificial Intelligence (DAI), where there are numerous as well as different types of complex agents. The agents have certain abilities (see below), using these capabilities to interact with other agents or change their environment, in order to solve group problems (Ferber 1999).

2.2.2 Agency

To introduce the term agent, a short but widely accepted definition of ‘agency’ is given by Jennings 2000, p. 280:

“An agent is an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives”.

Here, the term “autonomous” refers to the ability to make decisions without central influence of top-down control, and to respond to internal and external states of the system at run-time, which were not foreseen at design time. Thus, the agents’ nature is reactive, but can also be proactive at the same time, because they meet specific individual design goals and/or contribute to the goals of a higher organizational frame (family, enterprise, society).

Further, agents are ‘social’, which means that they interact with other agents. They might be designed to buy and sell or to exchange information with other agents or groups of agents. Agents are *reactive* if the agent is able to ‘perceive’ their environment and respond to it. Being communicative, by ‘sending’ and ‘receiving’ messages by some kind of communication language is a property of a complex agent. Pro-activeness refers to a goal-driven attitude, e.g. to maximize profit or contentment (Wooldridge 2000, Wooldridge & Jennings 1998). A further characteristic of agents is given by Epstein 1999. An agent is assumed to have a bounded reality. This means that an agent does not have global information, and does not have infinite computational power. Instead, agents operate in

an environment over which they have only partial control and observability. Many Agent-Based Simulations use simple rules based on local information.

Another pile of AB Models are rules which define the relationship between the agents and the relationship between agents and their environment; they are embedded in and interact with that environment (hunting, harvesting, soil degradation). Every agent consists of a set of rules, which can process internal states and 'sensor' external information, and translate them into states, decisions or actions (Parker et al. 2001). Their actions have consequences on their environment, which in turn may influence the action of the agent in the future (Figure 2-2).



Figure 2-2: Agent-environment interaction

2.3 Roles of Agent-Based Models

Axelrod & Tesfatsion 2005 identify four useful goals for agent-based simulation: empirical, normative, heuristic and methodological goals.

With an empirical goal in mind, the scientist tries to answer the question of how a special emergent large-scale structure has evolved and could persist. From social science, the example of standing ovations, trade networks or social norms is given. To explain this behaviour and these patterns, the researcher tries to reproduce macro-structures by defining rules at the micro-level.

The second goal is normative understanding. As already stated above, an Agent-Based Model can serve as an experimental laboratory. In this sense it can be applied for the evaluation of the performance of proposed policies, for exploring the design of institutions to be created or changed, or to investigate certain social or environmental processes. The aim is “the detection of good designs” (Axelrod & Tesfatsion 2005). Examples include design of auction systems, evaluation of environmental laws, environmental impact assessment etc. The simulation is equipped with privately motivated agents able to learn and adapt. These agents are trying to maximize their advantages through strategic behaviour. The aim of the simulations is to find a set of interaction rules which lead to a stable, equal and fair system, thereby avoiding that simulated individuals or groups can take too much advantage of certain situations for the disadvantage of others.

The third goal is heuristic. The researcher tries to get more insight into fundamental causal mechanisms of social systems. Even agent-based models equipped with agents that have very simple social interaction rules can generate a surprising outcome. With these simple rules at the micro level, it is possible to generate and explain macro structures, often referred to as ‘emergent properties’. Emergent properties are special ‘qualities’ of a system, which cannot be explained by analyzing single properties of the components or individuals constituting these systems. For example, in the segregation model developed by Thomas Schelling (Schelling 1978), simple interaction rules generated segregation patterns although the agents were “fairly tolerant”. Emergence cannot be predicted or understood from examining individual elements in isolation. It is rather the result of complex autonomous interaction of adaptive agents with their environment and with other agents, which explains these kinds of macro structures. In Agent-Based Modelling, the

individuals adapt to their physical and biotic environment, and at the same time are parts of the biotic environment of other individuals - a circular causality, which gives rise to emergent properties (Grimm & Railsbach 2005). Examples for explicitly spatial emergent properties, which result from human-environment interactions include urban segregation (Schelling 1978), suburban sprawl (Torrens 2003), ecosystem functions (Grimm & Railsbach 2005), social norms (Axelrod 1997) and paths of technology diffusion (Berger 2000).

A fourth goal is methodological advancement. To date, there is still no standard set of methods applicable in Agent-Based Modelling. Therefore, research effort is carried out exploring the suitability and applicability of different Agent-Based Simulation environments as well as exploring ways to validate and verify models and simulation outcomes. Much effort has been put into research to integrate other systems in AB-Simulation, such as GI-Systems (see Brown et al. 2005, Ferrand 2000, Holm et al. 2000, Gimblett 2002).

2.4 Components of an ABS

2.4.1 Environmental Model

Agents usually are embedded into a more or less well defined environment. An important distinction is made between spatially explicit and non-explicit environments (Hare & Deadman 2004). A spatially non-explicit environment can be as simple as a database representation. Not in all cases, there is need for a spatially explicit environment. Nevertheless, the introduction of a spatial explicit environment may be justified if interactions between agents and/or the environment exist, and if these interactions are distance-dependent, e.g. distance to water, distance to markets or, if these interactions are constrained by the biophysical spatial heterogeneity of the environment (land distribution patterns, parcel sizes). Another hint for spatial explicitness is given if the random rearrangement of components of the model results in a different behaviour of the system.

Models of land use and land use change dynamics often make use of a spatially explicit representation of the environment. There are two main concepts to represent space in Agent-based models: the raster and the vector model.

The Raster model is an abstraction of the 'real world' as a matrix. Hence, spatial data is divided into discrete units - a tessellation technique divides space into a mosaic of disjoint cells or 'shapes'. 'Regular' refers to the property of the cells that all have the same size, whereas 'congruent' describes the cells that have the same side lengths. The two most commonly used raster shapes are square and hexagonal cells (Figure 2-3).

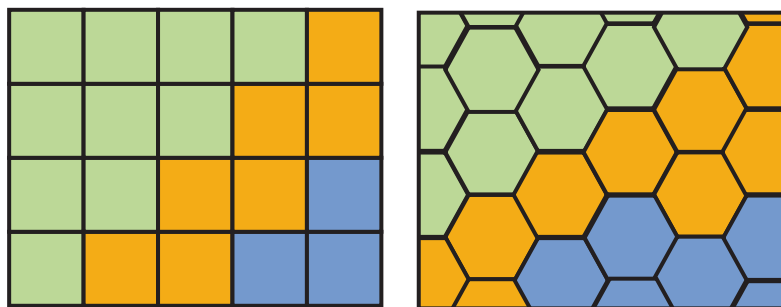


Figure 2-3: Regular and congruent raster representations. Left: square cells, right: hexagonal cells

The advantage of the raster data model is the representation of discrete and continuous spatial phenomena (Figure 2-4).

A well-known form of irregular tessellation is the region quadtree (see **Gatrell 1991**); however, the concept of irregular tessellation of space usually applies to vector representation of space.

Contrasting the raster space, with its uniform tessellation of space, the strength of the vector representation is its irregular approach (Figure 2-5). In the vector-based model, Geodata is represented as coordinates - pairs of numbers expressing horizontal distances along orthogonal axes, or triplets of numbers measuring horizontal and vertical distances, or n-numbers along n-axes expressing a precise location in n-dimensional space. Coordinates generally represent locations on the earth's surface relative to other locations. In vector data, the basic units of spatial information are points, lines (arcs) and polygons. A point can be described as a zero-dimensional abstraction of an object represented by a single x/y coordinate. Examples include pumping stations, cities etc. Following this, lines and polygons are composed simply as a series of one or more coordinate points. For example, a line is a collection of related points, and a polygon is a collection of related lines. Typically, each of the spatial entities has one attribute information or more pieces

of attribute information connected to them, e.g. through a link between the geometries and a database application (Fotheringham et al. 2000).

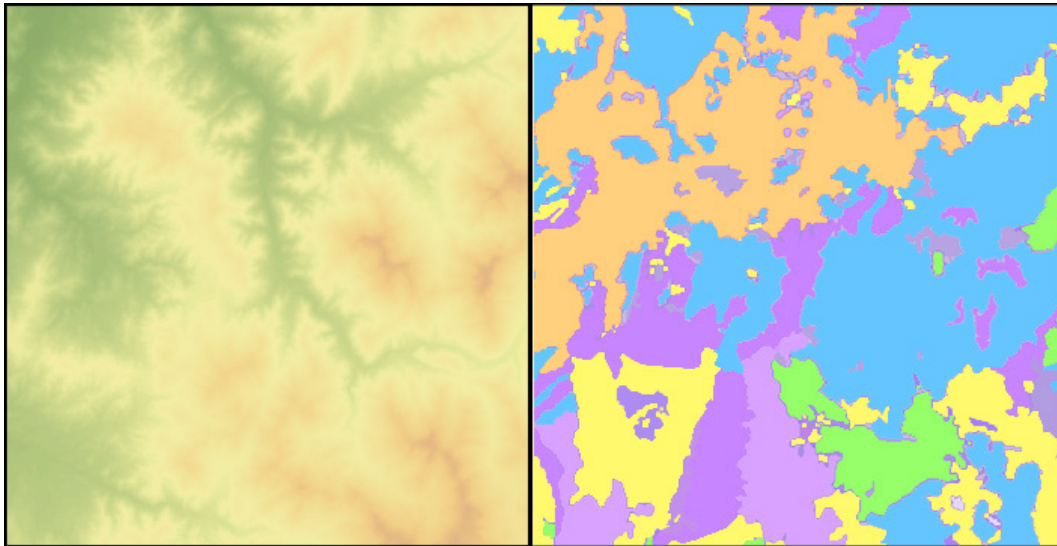


Figure 2-4: Continuous and discrete representation of attributes. Left: continuous elevation surface. Right: discrete land-use map.

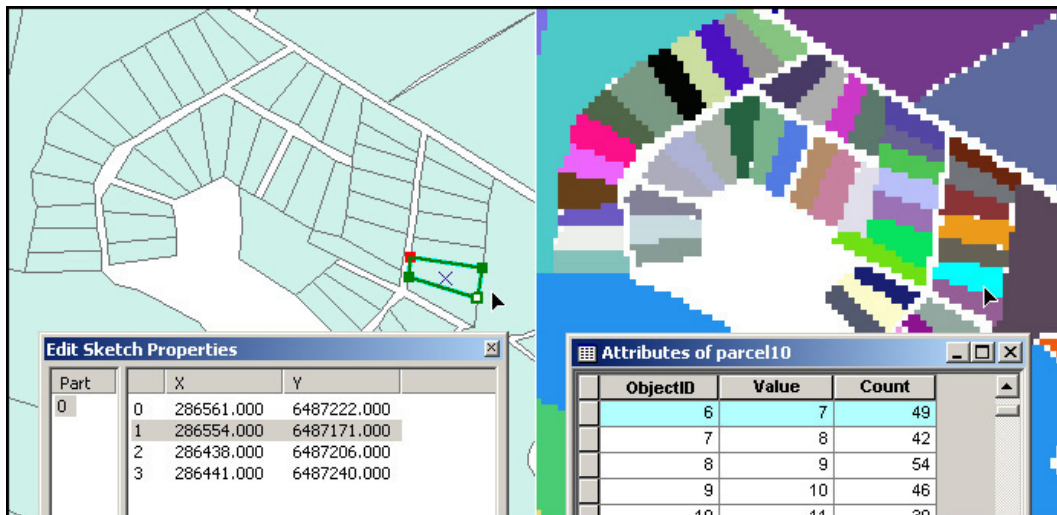


Figure 2-5: Vector (left) and raster (right) representation of parcel data.

2.4.2 Time

Agent-Based Simulation (ABS) frameworks have to handle representation of time through their discretization into time steps (Brown et al. 2005). Time units are specified depending on the complexity and data source, in order to calibrate the simulation to ‘real world’ dynamics.

There are three main possibilities to trigger actions in the ABS: The most common approach is to perform the agents’ actions at every time step. The agents are updating their internal states based on previous time. In addition to that, it is possible to model a parallel time scale, by introducing another ‘time layer’. This way, one or more additional actions can be performed at an interval, or only once at a specific time.

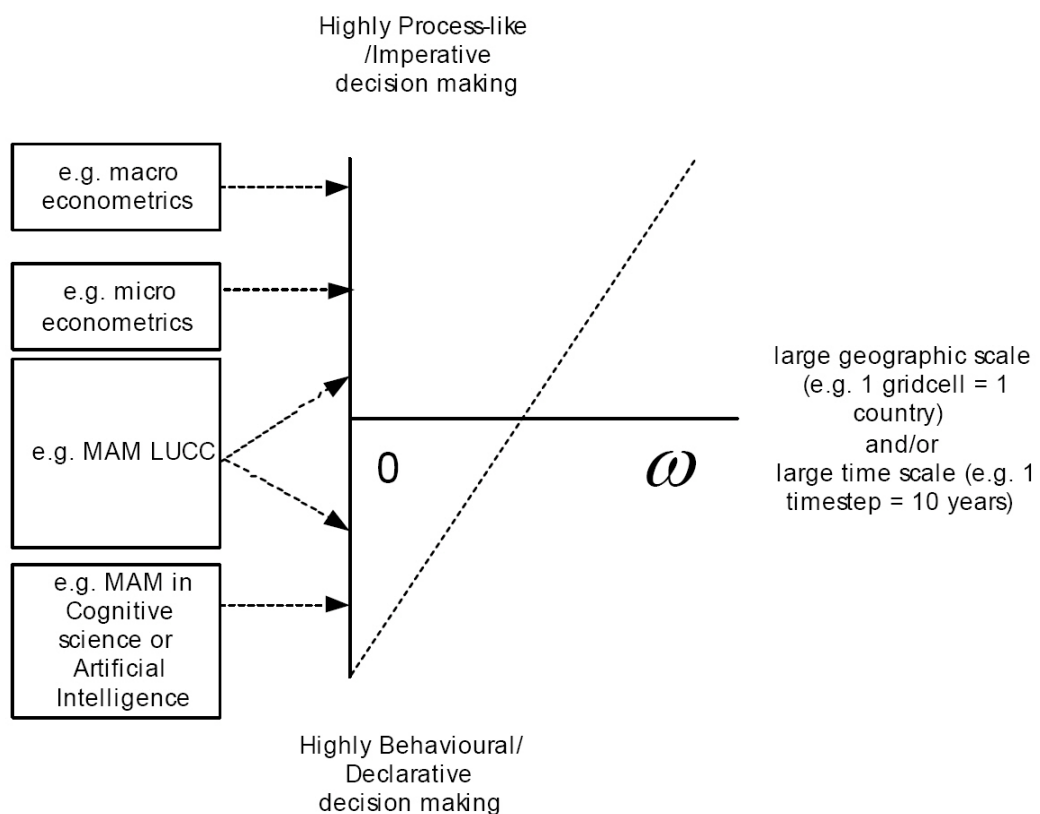


Figure 2-6: Gradient of possible decision model implementations (Parker et al. 2001, p. 56)

This leads to another concept of triggering the agents' action: That is, the event-driven approach, where an agent is acting only as a response to an event from outside. In this case, the agent checks its external or internal state at every time step, but triggers a certain action only if specific conditions are met.

Another way of scheduling agent actions is the asynchronous approach, where an agent's action is not performed at every time step, but may be fired randomly, based on a certain probability.

2.5 Micro-level Decision Making

Micro-level decision making is at the ‘heart’ of every Agent-Based Model. According to **Parker et al. 2001**, decision making ranges from process-like, imperative decision making to behavioural or declarative decision making (Figure 2-6). Imperative modelling refers to rules which result from “behavioural aggregation or process-description”, whereas in declarative modelling, the rules are “based on simple behavioural premise(s)” (**Parker et al. 2001**, p 50).

The first mentioned type of modelling is based on macro to micro economic theory. The geographic scale and/or time scale is rather coarse. For example, the model might be based on a cellular model with one grid cell being equivalent to one country and one time step representing ten years.

The other end of the gradient is characterized by behavioural or declarative decision making carried out by complex Multi-Agent Systems based on cognitive science or Artificial intelligence. The geographical scale is highly disaggregated; for example, interaction takes place locally between individuals. There is often a relation between the number of agents and the complexity and sophistication of the decision model (**Hare & Deadman 2004**). Whereas simple models can handle hundreds of declarative decision making agents, a complex imperative decision model might only consist of a few agents.

2.5.1 Declarative Decision Models

A commonly applied declarative decision model makes use of an *objective function*. Using objective functions, the agent is trying to maximize or optimize the outcome of the decision according to his goals. This type of decision making is widely applied for economic decisions within cost-benefit models where the agent is seen as a ‘homo economicus’, who has full insight into his environment, and therefore can choose the best decision that maximizes his outcome based on the given criteria.

These ‘best’ decisions imply that an agent always has the ability to access and process the required information free of barriers. However, this is rarely the case

in most of the decision situations. Full information access is not an appropriate assumption; for example, in cases where agents only have limited resources to access information. An agent might judge the fertility of his parcel based on experience, however, to be objective, he might want to measure certain parameters in a laboratory situation.

Another strategy, which refers rather to the ‘declarative’ end in Figure 2-6, is heuristic based decision making. Here, decision making of agents is based on a set of ‘IF-THEN’-rules or optimization trees (Parker et al. 2001, Hare & Deadman 2004).

2.5.2 Imperative Decision Models

A rather simple example of an imperative decision strategy of individuals is imitation. Imitation is based on the psychological theory of social comparison, where a person sees what peers do and then uses the same strategy as those he admires or as those who are successful in their behaviour.

Imitation of behaviour is used in many agent-based simulations as underlying behaviour theory. Social or ‘friendship’ networks can e.g. be represented by a grid in which the distance in the grid represents the strength of social relation. The stronger this relation is the more probable is that the agent is imitating the behaviour of the agent ‘nearest’ to him. In many cases, an agent decision imitating other agents can be based on the principle of success, which means that the strategy of successful agents is being copied. Another principle which might play a role is similarity, which means that an agent bases his action on agents that have similar needs, e.g. water use of farmers in the same irrigation sector.

Imitation can be a function of spatial proximity. Spatial proximity can have an effect on the spread of behaviour, as it is the case to neighbours, which are spatially close in their environment, like land managers sharing parcel borders with others, living in the same house or street. Like social networks, spatial proximity can be modelled by a grid, however interpreting proximity as distance and not as the intensity of social relation (Hare & Deadman 2004).

More sophisticated and more difficult to implement are complex adaptive agents. These types of agents are ‘intelligent’ and are able to learn. One technique is Bayesian learning, where the knowledge of prior events is used to predict future events (Parker et al. 2001).

2.5.3 Intrinsic Adaptation

A further interest of environmental modellers is how to explore the change in or emergence of agent behaviour over a longer period of time in response to environmental change. In addition to the adaptation that can occur through social interaction, it can also be a requirement that agents are able to adapt intrinsically, i.e. adapt their own behaviour through their own cognizance. For example, this can happen in response to other agents ‘near’ to them. The term ‘near’ either refers to a social network (friends, clients), or can be defined as spatial proximity (Hare & Deadman 2004).

2.5.3.1 Multiple Strategies

The designer of an agent decision model can choose among different decision models he wants his agent to implement. However, an agent is not limited to one model, but can choose among a set of different decision models. It could be possible to let the agent choose the type of model autonomously in reaction to the changing physical or social environment or based on global variables, e.g. population growth or meta rules (‘If times are bad...’) (Hare & Deadman 2004). With a growing number of decisions, the agent could learn to implement the ‘best’ strategy for any given situation.

2.5.3.2 Fine Tuning

Rather than choosing among different strategies, fine-tuning refers to small changes and updates in an agent’s decision making strategy. With fine-tuning, the agents update their knowledge base used for decision making, based on new information gathered from the environment or from other agents.

2.6 ABM Typology

Hare & Deadman 2004 reviewed 11 Models and analysed them based on the above mentioned concepts and characteristics. The authors came up with a typology (see Figure 2-7) by classifying Agent-Based Models based on three most important “requirements” they identified:

- the way social and environmental model is coupled
- social interaction
- intrinsic adaptation

The highest branch separates the models into spatially explicit and spatially non-explicit models. The authors believe that this is a fundamental decision to be made in an early stage of model development. The next level in the taxonomic tree classifies the models according to their social interaction strategies, ranging from relatively simple models, which do not have social interaction to complex models able to simulate group-based tasks. The lowest level classifies the models according to their intrinsic adaptation capabilities: none, multiple strategies and fine tuning.

The authors note that this rather general classification is able to integrate a wide variety of models, especially for environmental applications. The typology should serve a guideline for experienced developers as well as non-experienced developers in an early stage of modelling.

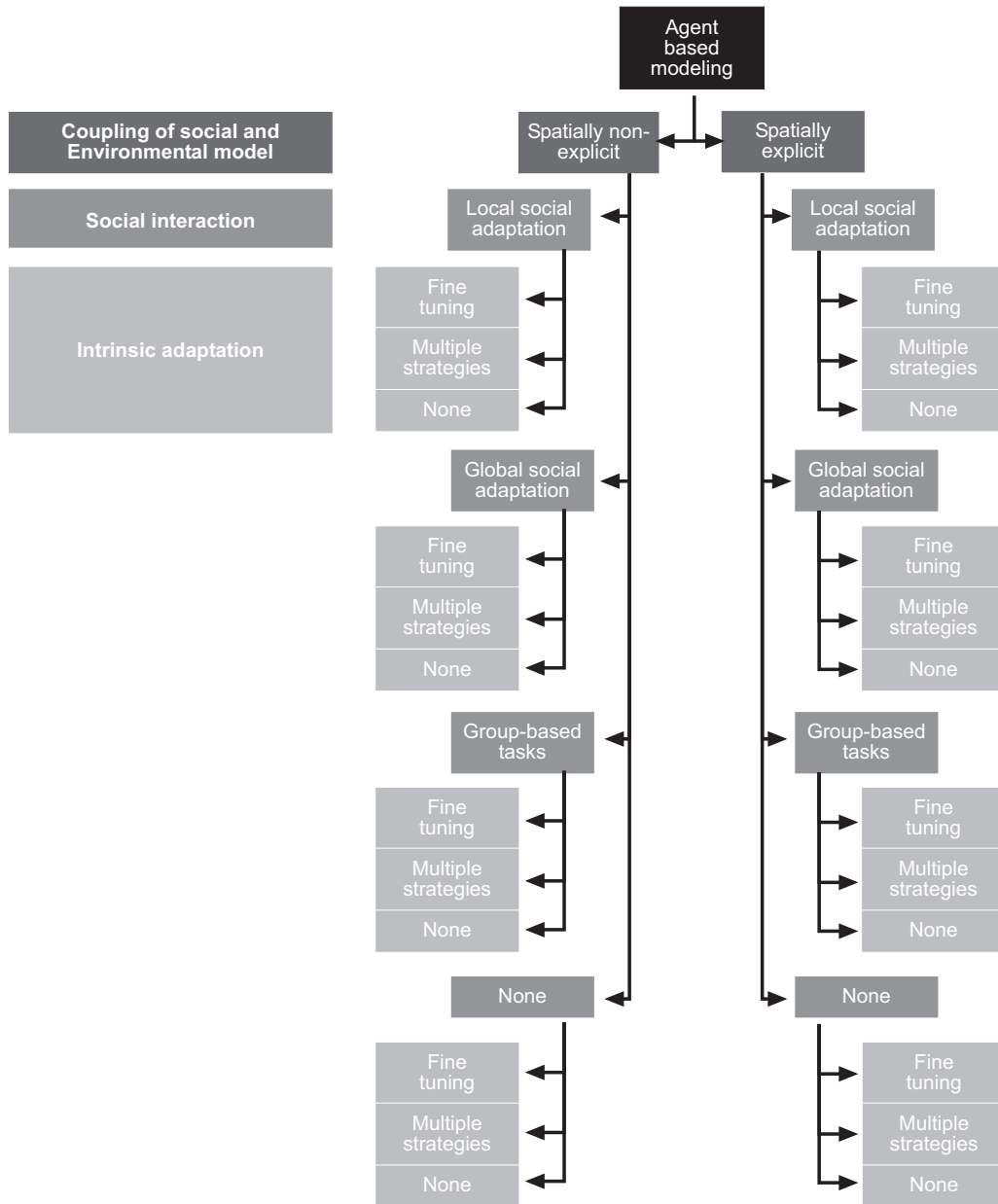


Figure 2-7: Typology of Agent-Based Simulation (adopted from Hare & Deadman 2004).

2.7 Technology

Regarding the technology side for the creation of ABM, the developer can choose from a variety of tools. Following the concept of **Sprague & Carlson 1982** (in **Gijsbers 2000**), where a framework for building decision support systems are proposed, an Agent-Based Simulation counterpart could be categorized into three components: tools, generators and simulations (Figure 2-8).

ABM tools

The first components are ABS ‘tools’, which consist mostly of coding libraries and components. The object-oriented approach is used in nearly all agent-based models. The most commonly used programming language is Java, C++ and Objective C. Less frequently but with growing application, Microsoft Visual Basic.Net and the Scripting language ‘Python’ are used. The object-oriented approach offers clear advantages over traditional linear programming techniques. The design of classes enables the programmer to assess the problem more directly and to express it better. With object-oriented programming, it is possible to describe the solution in the terms of the problem space (e.g. ‘the reservoir manager releases water’) rather than in computer terms, which is the solution space (‘Set the bit in the chip, which means that the relay will close’). The programmer deals with higher-level concepts and can do much more with a single line of code (**Eckel 2000**).

Simulation builder

Several groups have developed simulation platforms in which object-based computational models can be implemented. The most commonly used are SWARM (**SDG 1999**), RePast (**RePast 2003**), Ascape (**Parker 2001**) and CORMAS

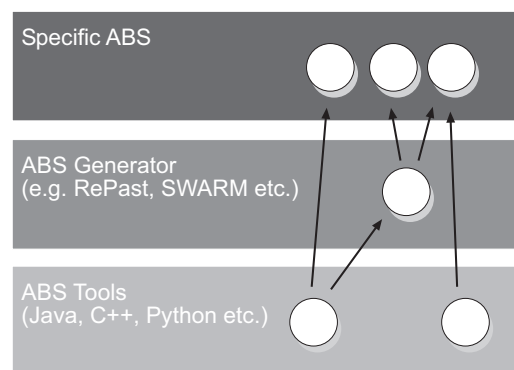


Figure 2-8: Proposed Agent-Based Simulation development framework (after **Sprague & Carlson 1982** in **Gijsbers 2000**).

(Parker et al. 2001), all written in object-oriented programming languages. For a comparison and more detailed description of the above-mentioned, see Parker et al. 2001.

A closer look is taken at the RePast simulation environment, as this toolkit is introduced later as the modelling framework (see Chapter 4). Information about the toolkit is drawn mainly from the official ROAD (Repast Organization for Architecture and Development) website (RePast 2003).

The Recursive Porous Agent Simulation Toolkit (RePast) is a free open source toolkit that was originally developed by Collier et al. 2003. It was created at the University of Chicago and has consequently been maintained by organizations such as Argonne National Laboratory. Repast is now managed by the non-profit volunteer Repast Organization for Architecture and Development (ROAD). The Repast system, including the source code, is available directly from the web (RePast 2003). Repast focuses on flexible models of living social agents, but also includes environmental models and other geographic applications.

The Repast toolkit, currently in version 3.1, is a specification for Agent-Based Modelling services or functions. There are three concrete software implementations of this conceptual specification that have the same core services that constitute the system. The implementations differ in their underlying platform and model development languages. The three implementations are Repast for Java (Repast J), Repast for the Microsoft.Net framework (Repast.Net), and Repast for Python Scripting (Repast Py). Repast J is the reference implementation that defines the core services. The first version of RePast was mainly based on SWARM (SDG 1999), but was written entirely in Java.

Repast is relatively well documented, as it includes a variety of agent templates and example simulations. However, the toolkit gives users complete flexibility as to how they specify the properties and the behaviour of agents, as it is fully object-oriented. Repast has a variety of features supporting Agent-Based Modelling in a scientific setup. The Repast event scheduler supports both sequential and parallel discrete event operations. Event-driven actions indicate that agents react to observed changes rather than just acting at specific times. Repast offers built-in simulation results logging. It is possible to export collected data at runtime by writing data into text files, movies and screenshots (PNG-Format). RePast provides a range of two-dimensional agent environments and visualizations. One of the advantages of Repast is the social network modelling support. Repast also includes libraries for genetic algorithms, neural networks, random number genera-

tion and specialized mathematics, as well as built-in systems dynamics modelling capabilities and integrated Geographical Information Systems (GIS) support through the Geotools libraries, a java based Open Source GI-System (**Geotools 2005**).

Specific Simulations

Some of the most prominent application fields of Agent-Based Modelling are sociology (**Epstein & Axtell 1996, Axelrod & Tesfatsion 2005**), artificial intelligence (**Jennings 2000, Langton 1988**), ecology & environmental modelling (**Grimm & Railsbach 2005**) and polycentric integrated projects (**Pahl-Wostl 2005**). However, it would not make sense to start describing individual models here or comparing them to the author's framework. The interested reader can turn to an excellent categorized comparison of eight recent research activities of young researchers in **Parker et al. 2001**. In the same publication, nine mature projects are described in the appendices. Another good source of model description and comparison is **Hare & Deadman 2004**. The authors analyse eleven Agent-Based Models and draft a typology based on the categorization of the findings (see also Section 2.6).

3 Spatial Decision Making

The objective of this chapter is to give a brief overview of the underlying concepts of spatial decision making. Especially those components used later in individual decision making are presented.

3.1 Overview

Spatial multiple criteria decision making is widely used as a framework for assessing suitability analysis and land allocation problems (Batty 1993, Czeranka 1997, Eastman 1993, Eastman 2003, Gijbers 2000, Leung 1997, Malczewski 1999). Special focus will be based to the somehow ‘classical’ approach used as a basis in many spatial decision support systems. According to this approach, the first step in multicriteria decision making is an exploration of the domain under study to identify the main system components and dynamics and to study the main problems. After this ‘knowledge elicitation’ step, the decision maker defines objectives which potentially help to solve the identified problems. As a next step, criteria relevant to these objectives have to be identified in order to weight them according to the decision maker’s preferences and experiences. Then, the decision maker applies an adequate aggregation rule, and finally comes up with a result – in the case of spatial decision making it is often a surface of aggregated usability or suitability indices. To verify these results, the decision maker might carry out some kind of sensitivity analysis (Malczewski 1999).

After introducing the main concepts of the mentioned spatial decision making process, the two different concepts - local and global decision making - are discussed in the context of decision making in Agent-Based Modelling.

3.2 Evaluation Criteria

Decision problems are hierarchically nested. At the top of the hierarchy stands the objective of a decision maker. Such an objective could be to find the best suited location for cultivation in order to minimize the production cost. At the bottom level there is a set of attributes. At least one, but usually more attributes have to be identified and evaluated. Every attribute must constitute a direct or indirect expression of the degree to which the objective is met.

In spatial decision making, attributes vary over space. While non-spatial attributes can be assessed with relatively easy spreadsheet calculations, the case of spatial attributes is more difficult. A common approach to structure spatial phenomena is by criterion maps. An important distinction is made between two types of criterion maps: *factor maps* and *constraint maps* (Malczewski 1999, Eastman 2003).

3.2.1 Factor Maps

According to Malczewski 1999, p. 342, a factor map is “a map layer in the GIS database representing the spatial distribution of an attribute that measures the degree to which its associated objective is achieved”. From the data model viewpoint, factor maps can be based on the raster or vector model. Most spatial decision making applications apply the raster model. Therefore a factor map usually consists of a cellular rectangular raster which holds binary, discrete or continuous variables. A single value is assigned to each cell often referred to as deterministic factor map. Examples of factor maps are slope maps or soil fertility maps (Malczewski 1999).

3.2.2 Constraint Maps

The counterpart to factor maps are constraint maps. In real world problem situations, there are constraints to the decision alternatives, which separate the decision alternatives into two categories: Those who can be considered as a decision variable (feasible) and those who are not (infeasible). From the spatial decision making viewpoint, constraints are conceptualized into constraint maps which often consist of a spatial distribution with binary values. Locations, where decision alternatives are feasible carry the attribute 1, whereas locations with an attribute 0 are infeasible. Examples for spatial constraints include buffer zones or land use restrictions.

3.2.3 Standardization of Criterion Maps

In order to compare the different attributes, it is necessary to standardize the decision attributes to a comparable scale. **Malczewski 1999** outlines four approaches to create factor maps: linear scale transformation and the value/utility function approach are applied mostly to deterministic factor maps. The probabilistic approach can generate objective, subjective or revised probabilities.

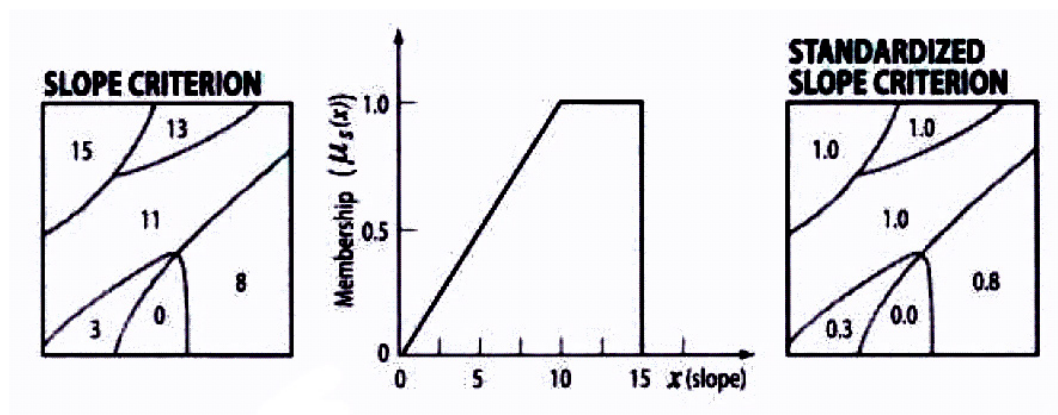


Figure 3-1: Criteria map standardization with fuzzy membership approach (**Malczewski 1999**, p. 131)

The fuzzy membership function approach is examined in more detail, as it is used to generate factor maps for the Agent-Based Model in the case study of this work. The procedure of standardizing a criterion map based on fuzzy sets is best explained by following an example given in **Malczewski 1999** with a slope criterion map (see Figure 3-1). The slope criterion map displays the slope gradients in percent as regions. For the objective of finding the best location for agriculture activity, a steep slope is an undesirable condition. As it is unrealistic to exactly determine where to divide steep and not steep, a fuzzy number is used. The fuzzy membership approach translates the slope gradient values to a value between 0 and 1 representing the membership to the linguistic value 'steep slope'. For example, a slope value of 0 has a membership value of 0; therefore a plain terrain is 100 percent *not* a steep slope. However, a slope value of 10 or more percent *is* considered as a steep slope, and therefore it is corresponding to a membership value of 1. Everything in-between can also be termed as a steep slope, but only to a certain degree, for example with a membership value of 0.5 where the slope is 5 percent.

3.3 Multiattribute Decision Rules

Once the attributes for decision making are identified and standardized, each attribute will be weighted according to its relative importance in the decision making process. After this, an aggregation rule is applied to order or rank the decision alternatives. As it is the case with standardization methods, there are various techniques including *Simple Additive Weighting*, *Value Functions*, *the Ideal Point Method*, *Concordance Methods* and *Fuzzy Aggregation methods* (Malczewski 1999).

Only the first, *Simple Additive Weighting* (SAW) will be explained here, as the farmer agents in the later described Choapa Model apply this method for spatial decision making (see Section 4.5.5.4).

The SAW method is also referred to as *weighted linear combination* or *scoring method*. It is based on the concept of a weighted average. For each decision attribute, a weighted standardized map is calculated by multiplying the standardized decision attribute by the assigned weights for each factor (Malczewski 1999). The next step is to summarize all weighted standardized maps (see Figure 3-2). In the example the two criterion maps are standardized to a common scale between 1 and 3. Each criterion map is assigned a weight value between 0 and 100 percent, which represents the influence of the criterion. First, the cells are multiplied with their weight and then summed up to create the output raster. For example, the middle cell of each input raster is multiplied by the weight value $\text{inras}_1=0.75$ ($1*0.75$) and $\text{inras}_2= 0.75$ ($3*0.25$). The sum of 0.75 and 0.75 is 1.5. The final value in the example is rounded to 2 (see ESRI 2005). The decision alternative with the highest score is the best alternative.

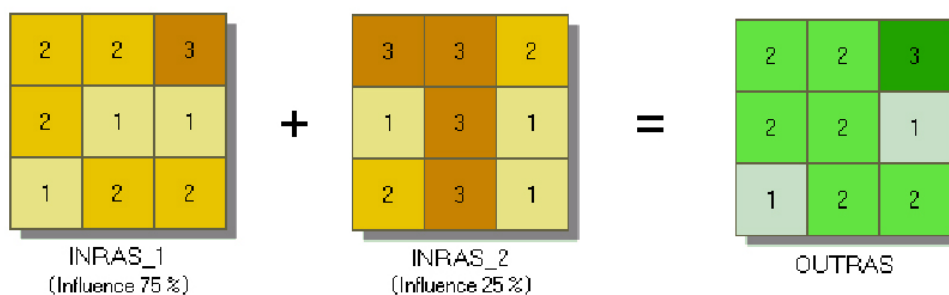


Figure 3-2: Weighted linear combination or scoring method of two criterion maps. Graphic adapted from ESRI 2005.

3.4 ‘Global’ and ‘Local’ Decision Making

3.4.1 ‘Global’ Decision Making

In ‘Global’ or ‘Macro-level’ decision making, the decision maker has full insight and information about the defined decision space. Consequently, he applies his decision model to every single micro-location in the study area. The result is an expression of preference of a single person or a group of people. In many cases, this is a powerful approach for resource allocation in spatial planning, where decisions are centralized especially in the policy sector or in big companies.

Nevertheless, this kind of assessment has only limited capabilities when it comes to explaining how these structures evolved on the local level. There are complex (spatial) interactions between land uses and actors, which often result in emergent land use structures. So, in many cases, the real-world distribution of land use differs in many cases considerably from the potentially optimal distribution because it is based on a set of rather subjective criteria of one decision maker.

Furthermore, a ‘snapshot-type’ analysis in which a system state is considered only at one given time does not consider that the suitability at a given location might change with time. Under certain conditions, locations with a high suitability might as well be those which show the strongest dynamic. Then short-term changes will invalidate the global decision model.

3.4.2 ‘Local’ Decision Making

One of the shortcomings of the ‘global decision making’ approach is the assumption that all factors are equally important in every location and do not change over time. Not in all cases this assumption adequately supports the research concept. In the case of discrete agents, normally every individual has his own set of dynamically changing preferences. These preferences are a function of the perceived environment (e.g. soil suitability, water resources), global variables like market prices and the social interaction with neighbours and other individuals of his social network (e.g. imitation behaviour). For example, soil suitability might be an impor-

tant factor for traditional campesino economic framework, which is e.g. the cultivation of corn; but it is to a lesser degree important where the adequate use of fertilizer can compensate for sub-optimal fertility, as it is the case in modern fruit or wine production under irrigation. Therefore, the concept of suitability applied to a spatial system is not an absolute measure for the entire space, but can vary within it, and is therefore to be seen as a relative value, depending on the objective and subjective perception of the individual farmer.

To a certain degree, the Agent-Based approach can overcome these shortcomings, because it permits the simulation of distributed decision making in time on the micro-scale by embedding the mentioned procedure, the 'decision model', into every single actor. That way, the simulation can integrate the concept of decision making based on spatially varying factors as well as decision making based on different preferences of the individual decision maker.

4 Case Study

After having presented the theoretical foundations of an Agent-Based Simulation framework, and of Spatial Decision Making, the following part is dedicated to an applied case. This chapter describes the modelling and implementation process of a case study in the Choapa Valley in the fourth region in Chile.

4.1 Study Area

The study area is a small area located in the northern part of Chile, also known as the Coquimbo region (Figure 4-1). The general spatial structure consists of four entities: the coastal strip, the cross-sectional valleys, the pre-mountain range and the mountain range of the Andes. A series of East-to-West oriented valleys transverse the region from the Andes to the Pacific Ocean. The main valleys are Elqui, Limarí and Choapa Valley. The appearance of these valleys significantly contrasts their surroundings as they are densely cultivated under irrigation, whereas the surroundings are characterized by dry maquis-like vegetation known as 'mattoral'. Therefore, the region is frequently called the "Green North".

The Region has a population of 608,000 and a density of 14.8 inhabitants per km² (INE 2002). The majority of the population, about three quarters, live in six major cities: Coquimbo, La Serena, Vicuña, Ovalle, Illapel and Salamanca. Settlement patterns show a concentration along the main rivers in the biggest valleys Elqui, Limarí and Choapa.

Economic activities are mostly agriculturally oriented and cover an area of about 850,000 ha (INE 1997). This corresponds to an area of only 10 percent. The main products are fruit that is exported and grapes for a special Chilean brandy ('Pisco'). Though not quite as important, horticulture and flower plantations may be mentioned. Nearly 80 percent of agricultural activity is based on irrigation agriculture.

The regional climate is dominated by the southeast Pacific anticyclone, which almost always blocks the frontal precipitation systems. As a consequence of the persistency of the atmospheric circulation system, the Coquimbo Region is characterised as a semi-arid to arid climatic zone (Ferrando 2003). As a result, a remarkably cloud-free atmosphere in the interior valley brings about extremely high solar radiation values.

Especially during the summer months, the region shows a strong hydrological deficit. The period varies between 8 and 12 months. Aridity increases towards the interior due to a strong climate gradient. Annual precipitation varies between 25 and 420 mm per year and occurs in the winter season. A general spatial variation can be noticed; the amount of rainfall is increasing from North to South and decreasing from West to East.



Figure 4-1: Study area.

4.2 Problem Framing

Human economic activity and security in the Coquimbo region is strongly related to climate variability and access to water for irrigation (water rights), and is being controlled largely by access to capital and irrigation technology to improve water efficiency. Public policies related to the development of irrigation infrastructure (i.e., dams and canals) were put in place in the Coquimbo-Region in the early 1920s, as a means of securing agricultural activity and to mitigate short term climate variability. However, the development concentrated on the Elqui and the Limarí-Basin, which both show a good coverage of irrigation infrastructure whereas the third main river basin of the region, the Choapa Valley, is still underdeveloped.

Due to the above mentioned climate variability, the low irrigation security and associated high risk of production loss distract professional farmers from investment in the agricultural sector there. As a result, the Choapa Valley is still characterized by farmers that have relatively small parcels and that produce mainly for subsistence or as small commercial producers.

To improve the situation, and to follow the example of the other two valleys of the region, policy is promoting the construction of two dams, the 'Corales'-Dam, which is at the moment in the process of filling up, and the 'El Pato'-Dam, which will be finished within the next few years. The construction of the latter will increase irrigatable land by an additional 13000ha in the valley. It is expected that national and international medium and big agricultural enterprises will be attracted into the valley. This process will be paralleled by an internal socio-economic restructuring, because some of the existing farmers are seeking to receive new water rights, extent agricultural surface and invest in modern irrigation technology, while trying to compete with the above-mentioned external agro-businesses.

However, the Coquimbo region is facing a pronounced natural and human desertification process, as the nearby Atacama Desert is spreading towards the south. Furthermore, there is empirical data showing that precipitation is constantly declining, as it is the case for La Serena and Coquimbo, the capital of the Region. Therefore, long-term climate change affecting the availability of water in the next decades is an imaginable scenario. The national water board claimed that, "...from

the second region to Puerto Montt, in the tenth Region, precipitation will decrease up to 20-25%” within the next two decades (DGA 2004, DGA/MOP 2000).

Under these circumstances, it is necessary to explore the effects of climate variability on the irrigation agriculture system by dynamic modelling, taking into account the main system components. The model should be capable of exploring the effect of different climate scenarios.

4.3 Data Sources and Quality

Knowledge engineering started 2004 during a field trip to the Choapa Valley, where the author gained insight into socio-economic history, structures and processes. This essential step helped understand the problem context of the Valley and the whole region. Especially for an agent-based model, it is of advantages to study the system and the later modelled agents in a ‘real world’ context before model implementation.

The observed GIS datasets for the region generally lack accuracy, coverage, consistency, documentation and metadata, making it difficult to generate a consistent dataset as an input for the model. This is especially true for analyzing change dynamics, as the datasets lack consistency between the different census tracks. For example, reference codes between the socioeconomic census tracks of 1982 and 1992 were completely different. Further, the spatial delimitation changed, making a comparison somewhat difficult.

Data is collected on a relatively disaggregated level (household units). Unfortunately, there is no digital spatial representation for linking the tabular data to a map view. A GIS-Dataset only exists up to the ‘district’ level.

Official agriculture census data (INE 1997) was collected five years later than the socioeconomic data, making it difficult to relate the two data sets. Further, the census data is given out only on the ‘municipality’ level, which is even coarser than the socioeconomic data.

Nevertheless, it was possible to create a knowledge base which was generated out of different empirical studies and datasets, unstructured interviews and text analysis. For some of the agents attributes, a pseudo-random number generator was

used to simulate certain attributes that are described later in context. An overview of the different data sources and their target uses gives Table 4-1.

4.4 Pseudo-Random Numbers

The simulation of some of the farmer attributes are governed by a series of ‘pseudo-random’ numbers, a technique widely used in computer modelling to handle uncertainty. The number generator creates a list of numbers which, when examined, do not show any rule of variation. Yet, they are *pseudo-random* because it is possible to exactly reproduce the whole series exactly, by specifying a small amount of information called random seed. The whole simulation will be reproduced exactly if the random seed is preserved untouched and, of course, the model and the initial parameters are also unchanged. If the random seed is changed the model reacts unpredictably, however within certain ranges of variation.

Table 4-1: Data sources used in the Choapa model.

	Agent Decision model	Agent data set generation	Spatial model	Hydrological model
CIREN 2001		X		
Brown & Peña 2003			X	
Camus & Rosenblitt 2000	X			X
DGA 2004		X	X	X
Personal interviews	X	X	X	X
Ferrando 2003				X
Cabezas & Payacan 2005		X	X	
León & Flühmann-Garay 2005	X			X
Paavola & Adger 2004	X			
INE 1992, INE 1997, INE 2002		X	X	
IPCC 1998, IPCC 2001				X

4.5 Model Description

The purpose of this section is to describe and explain the model and its dynamics in detail. First, an overview over the technical qualities of the model will be given. Then the position of the model will be defined within the typology proposed by **Hare & Deadman 2004** (see Section 2.6). Then the classification according to its *role* will follow. After this, the main system dynamics will be explained. An important part of this chapter is the description of the classes and the dynamics they add to the simulation.

4.5.1 Overview

The Choapa Model is an agent-based model making extensive use of the Java libraries of the Repast Simulation Framework (**RePast 2003**) as the code base. It is completely java-based and consists of five classes¹. As a production environment, the Open Source software Eclipse (**Eclipse 2005**) was chosen, as it assists very efficiently in the coding and debugging process.

The theoretical design of the model was done following the work of **Hare & Deadman 2004**. The authors define requirements for an agent-based model; guidelines for researchers new to the field to position themselves in the still wildly growing field (for a detailed description of these requirements see Section 2.4).

A main requirement is having an *environment* in which to embed the agents. The Choapa model uses a spatially explicit environment. A cellular 2-dimensional model is created, consisting of various ‘raster spaces’ holding the spatial attributes the model works with (see Section 2.4.1). The model uses ‘real world’ GIS-data as

¹ The entire code consists of more than 2000 lines of code. It is obvious, that this is too much to be printed in the annexes. However, a copy of the source code, with extensive documentation, is attached in the original version, and interested reader can receive a copy of the source code upon request (email: g-grill@gmx.net).

input. It does so by loosely coupling to GIS-software, like ArcGis (ESRI 2005) and IDRISI (Eastman 2003), through the import and export of ESRI ASCII text files. The built-in model builders of ArcInfo and IDRIS were used (see Section 4.5.6.1). The IDRISI software was utilized because it has advantages over the Model Builder of ArcView - it provides the user with a powerful and easy-to-manage component for defining fuzzy sets and creating factor maps based on these sets.

Another requirement is *micro-level decision making*. The Choapa Model uses a combination of rule-based decisions and objective functions. The rule-based component triggers certain migration dynamics. An objective function tries to minimize the cultivation costs of an agent. Cost is seen as a function of distance to water/irrigation infrastructure and slope. By evaluating his parcel, the farmer calculates the location with the minimum cost by 'simple additive weighting' of the two factors. Every farmer has his own set of preferences according to his technology level, and dynamically changes these preferences on adaptation.

Social interaction is mentioned as a requirement for ABM, although social interaction is not implemented in every model. The Choapa Model prototype does not use social agents so far; however it is planned to use a kind of local social interaction. It is argued that the farmers' decision model should take into account the behaviour of the agents' neighbours. Neighbour imitation should be part of the Choapa Model in a mature stage of development stage, because it is considered as important when simulating processes like migration or technology diffusion as it is the case with the model.

Intrinsic adaptation of decision making and behaviour is mentioned by Hare & Deadman 2004 as a component. Here, the agents update their decision making capabilities independently from other agents, and thus as an intrinsic process in order to adapt their decision making based on their own knowledge. The Choapa Model uses such an adaptation process. Based on the agents' technological capital, the agent has different demands on his environment. This results in spatial preferences with regards to the most suitable location for agriculture activity within his parcel. During the simulation, the agents constantly *fine-tune* their spatial decision making engine depending on their technology level as well as on the available water resources (see Section 4.5.5).

According to what has been said, and based on the typology of Hare & Deadman 2004 (see Section 2.6), the Choapa Model can be categorised into a spatially explicit model which does not use social adaptation so far, but relies on a spatial mi-

cro-level decision making engine which uses fine-tuning as a local adaptation strategy.

4.5.1.1 Role of the Model

Possible roles of Agent-Based Models have been discussed in Section 2.3. The Choapa Model should be seen as a computational laboratory, a “comptorium” (Parker 2001) to explore the impact of initial conditions and parameter values on macroscopic outcomes rather than as an empirical model. The empirical basis of the model does not allow for prediction at the current stage. In this sense, it is a rather abstract model, which helps to derive stylized hypotheses. However, after further improvement, the model should move from a simple explorative model to a complex empirical model, which can be used as a ‘management flight simulator’ for decision makers. This type of model can then predict possible impacts of decisions on the system under study.

4.5.1.2 Basic System Dynamics

Although the Choapa Model is not a pure systems dynamics model, it shows some basic dynamics, which will be illustrated by the typical notation (Figure 4-2). The Choapa Model system dynamics are the following: It consists of two shadow variables, ‘climate variability’ and ‘climate change’ as main exterior determinants and a balancing loop with four stocks: ‘reservoir level’, ‘available water’, ‘cultivated land’, and ‘agriculture water demand’. The stock ‘water rights’ is influenced by the precipitation pattern and is connected to ‘agriculture water demand’.

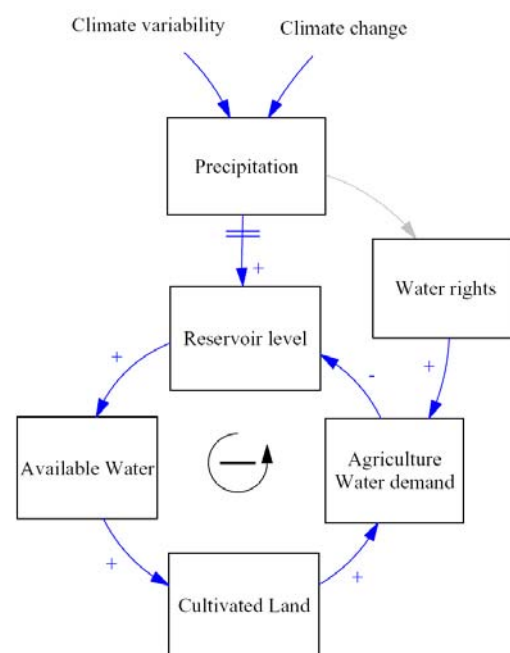


Figure 4-2: The Choapa model basic system dynamics.

The starting point of the dynamic model is the precipitation class. The given climate variability influences precipitation patterns, resulting in a certain amount of

rainfall per year. The model assumes that climate change affects precipitation patterns as well. There are parameters available to control the amount of precipitation, the variability and annual increase or decrease of precipitation.

The grey arrow in Figure 4-2 indicates a connection with the amount of water rights. The regional climate controls the long term distribution of water rights. In addition, the amount of water rights is balanced by the annual amount of available water.

With a delay, the precipitation flows into a reservoir. This is where a balancing loop starts. The more precipitation is available, the higher the reservoir level will be. However, as the reservoir capacity is limited, an overflow might occur in some of the years. This overflow can be used for agriculture depending on the capacity of the distribution system to a certain degree. The 'available water' compartment is positively connected to the amount of cultivated land. Thus, the more water is available, the more land can be cultivated. This increases the demand for water, which consequently decreases the reservoir level.

4.5.2 Model Class

The purpose of this section is to describe the internal structure and functioning of the Choapa Model. The Model consists of five classes. The classes' main parameters and functions will be described. Figure 4-3 gives an overview of the Model. The figure shows the five main classes, each represented by a box. Each box will be described separately in the following sections².

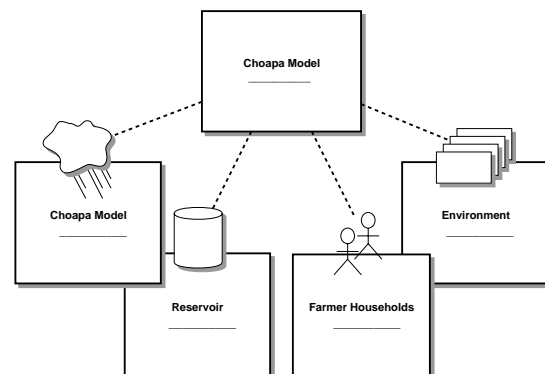


Figure 4-3: The Choapa Model class model overview.

² Extensive documentation of the source code is additionally provided as a digital resource on CD-Rom generated by Javadoc. Javadoc is a software tool from Sun Microsystems for generating documentation into HTML format directly out of comments in the Java source code.

The Model class can be seen as a ‘Metaclass’, which coordinates all actions related to the model flow. The Model class initializes the model and coordinates the model’s actions at runtime.

4.5.2.1 Model Class Parameters

Figure 4-4 shows the most important parameters of the model class. These parameters are part of the model class because they are used as initial variables in the graphical user interface, and can be changed there before each model run and during the simulation. Internally, these parameters are static variables; for example, when the precipitation class is called, a new object of that class is built and a precipitation event is fired, the constructor and the method *rainfall-Random()* makes use of the static variable of the model class ‘mean precipitation’ and ‘climate variability’ to calculate a precipitation value.

The purpose of this section is to describe these variables. However, as mentioned above, the interaction of the parameter with the other parameters and variables is not processed in the model class, but in the other classes. Therefore only an introduction will be given and each variable will be described in its context in more detail in the corresponding class descriptions.

The parameter *mean precipitation* represents the mean annual amount of rainfall in millimetres.

The *climate variability* parameter represents the standard deviation of a series of precipitation events in the study area. A default value was calculated using a spreadsheet calculator. If the user wants to simulate higher precipitation variability, he may alter this value.

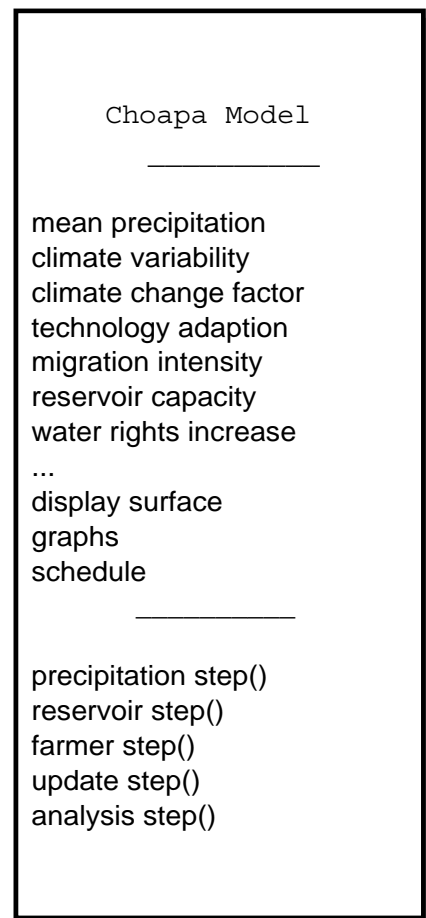


Figure 4-4: The Choapa Model class parameters and functions.

The *climate change factor* parameter provides the model with the ability to simulate long term climate change dynamics. If the user enters a value here, the value alters the precipitation each year by the given percentage. According to the given climate change scenario by the local water board, usually a negative value will be entered in order to reflect the decreasing precipitation in the future.

Technology adaption is a parameter which adds adaption capabilities to the agents' decision making model. This is based on the assumption, that there is a technology diffusion process going on in the valley. So far, the water efficiency for the whole region is only in a range between 28 and 48 percent (Ferrando 2003, DGA 2004). The model simulates the technology diffusion process by accelerating it on decreasing water resources, assuming that investment in water saving technology is the main response to water shortage. Whether or not this is a realistic assumption and how well it represents the real system is discussed later in Section 4.5.5.

The variable *migration intensity* is a parameter, which gives additional dynamic to the model. The model is assuming that there is an emigration process if the region's medium term precipitation pattern causes a water shortage, which causes the water reservoir level to drop. The described is a common pattern in the region (for a detailed description of the process see the farmer class in Section 4.5.5).

The parameter *reservoir capacity* represents the maximum capacity of the reservoir, which is passed to the reservoir constructor when the reservoir object is created (see also Section 4.5.4). With the parameter *water rights increase*, the user can increase the total amount of water rights³ (see Section 4.5.4).

The parameters *display surface*, *graph* and *schedule* are object parameters, which will be described in the following section.

4.5.2.2 Model Initialization

The model class coordinates all actions related to the model flow, initializes the model and coordinates the models actions at runtime (see Figure 4-5).

³ A water right is a water unit in the state water allocation system. With one water right, the farmer is allocated a certain amount of water, which he can use for irrigating his parcel. Normally one water right represents about 1 litre of water per second.

The Model class first initializes the simulation by creating the objects that interact in the simulation: a reservoir, a precipitation object, 287 farmer household objects and an environment with different information layers ('RasterSpaces') as attributes. The class variables are set and the objects are assigned initial attributes.

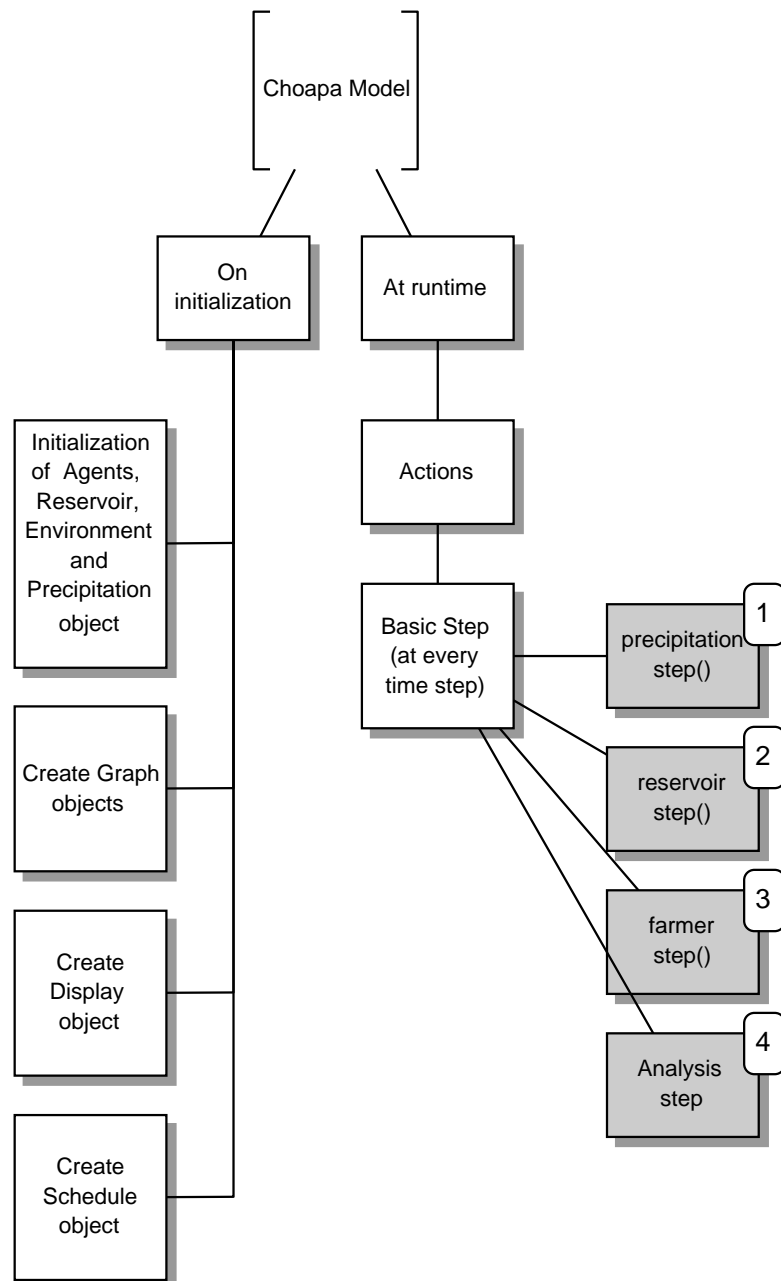


Figure 4-5: The Model class. The different steps are described in detail in **Section 4.5.3, 4.5.4, 4.5.5 and 4.5.6.**

The Model then creates a graphical user interface, which consists of four components. The toolbar (Figure 4-6) enables the user to control the flow of the simulation.

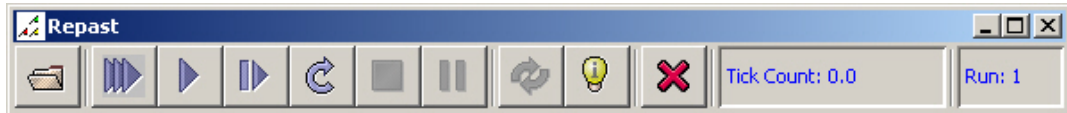


Figure 4-6: Control of the simulation: The Repast toolbar.

The settings pane (Figure 4-7) shows the initial parameters of the model, which can be altered by the user. Within the settings pane, custom actions can be defined, for example, a button can be inserted to fire a certain action at runtime. Furthermore, the user can carry out repast actions, which consist of creating additional graphs, taking snapshots and 'movies'.

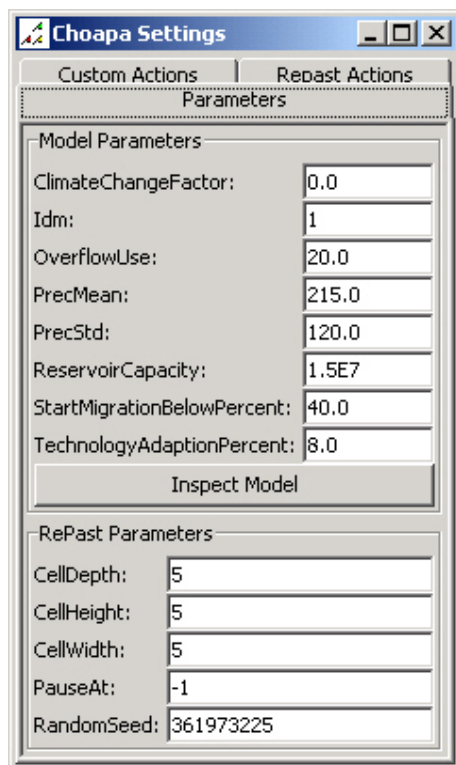


Figure 4-7: GUI of the RePast modelling framework. Initial parameter settings.

The display surface is the window in which the agents operate (see Figure 4-13, 58). It is initialized and populated with the relevant information layers which are represented by the RasterSpace Objects of the Environment class (for example cost RasterSpace, parcel RasterSpace, AgentSpace, etc.). The display surface is updated at every time step.

Apart from initialization of the model, the Model class controls the flow of actions through scheduling. The repast libraries actions are defined in the BasicAction class. Every action is scheduled through a ScheduleObject. The ScheduleObject defines *when* the corresponding action is fired. In the Choapa Model most actions are triggered at every time step; however a few actions, mainly for data collection are fired once, either at the beginning or at the end of the simulation. The graph objects are created and initialized. The graphs map the user defined variables to time steps (for an example see Figure 4-13, p. 58).

4.5.2.3 The Model's Basic Actions

On the left side in Figure 4-5, the models relevant basic actions, called 'steps' are shown: *precipitation step*, *reservoir step*, *farmer step* and *analysis step*. The actions are triggered one after the other according to the numbering. At each time step (=year) the model runs through the four basic steps. Each basic action implements a number of class functions or methods. For example, the precipitation step (see grey box with number one, Figure 4-5, left) implements the actions taken in the precipitation class (see Section 4.5.3).

4.5.3 Precipitation class

4.5.3.1 Parameters

The precipitation class simulates the climate in the model. There are two simulation modi the modeller can choose from: the modeller might want to base the simulation on real world data, or he might want to simulate rainfall based on a *uniform random* function, with a given value for the mean and a standard deviation. The simulation is based on real precipitation data for the first 42 years, and then continues with *pseudo-random* simulated values.

4.5.3.2 Calibration

Real world data for the study area was extracted from a database from climate station data from **DGA 2004** (see Figure 4-9). There is a strong similarity between the average of the region, which was calculated from 11 climate stations of the region and the Limahuida station. The Limahuida station can therefore be seen as representative for the study area. The *uniform random* function for simu-

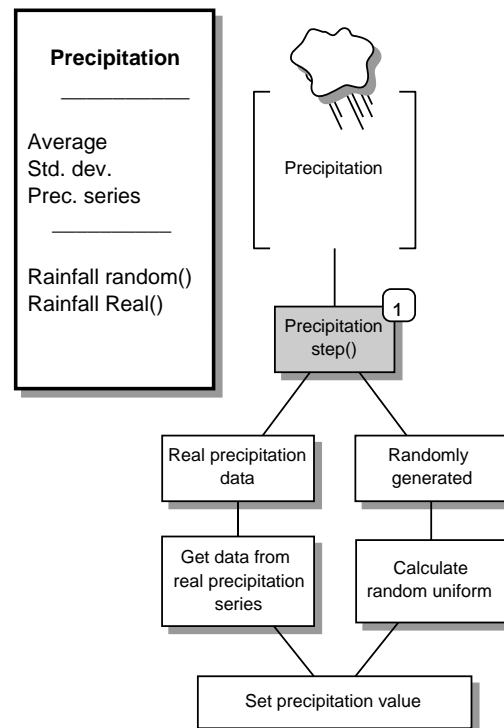


Figure 4-8: The Precipitation class parameters and functions.

lating rainfall was calibrated using the mean rainfall and standard deviation from the Limahuida station. According to this, the mean precipitation is 215mm and the standard deviation being 120. These values are set as initial parameters for the simulation. An example for a 100 years simulation is shown in Figure 4-27.

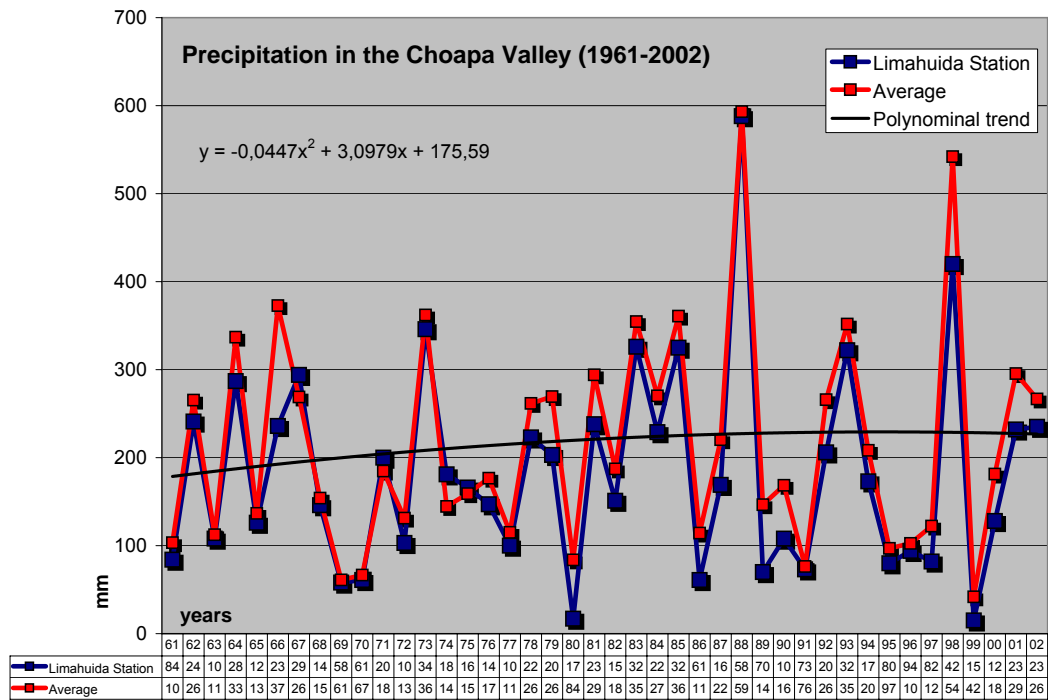


Figure 4-9: Annual average precipitation patterns for the lower Choapa Valley and for the climate station in the study area (DGA 2004).

4.5.4 Reservoir class

4.5.4.1 Parameters

Further dynamic is introduced by the reservoir class. Figure 4-10, on the left, shows the main parameters.

The parameter *capacity* defines the total volume of the reservoir in hectolitre (m³). The size of the reservoir was calibrated using the amount of *water rights* (span.: derechos de agua) available in the study area. In the privatized water market of Chile, a water right gives the holder the right to use a certain amount of water. The unit is litre per second and one water right roughly corresponds to the right to use 1 litre per second. In addition, there are *possible water rights*, which give the user the right to use water when the water supply is higher than the demand.

The total water demand in the study area was then calculated by summing up the water rights and recalculating the amount of water per year. The prototype of the model does not take into account other water uses (industry, domestic use etc.). However, the vast majority of water rights are utilized by the agriculture sector (see Table 4-2).

The variable *inflow* represents the inflow of water from precipitation. As there is no real measured data for the study area, a simple relation was established between the precipitation and the reservoir capacity. It was assumed that the average

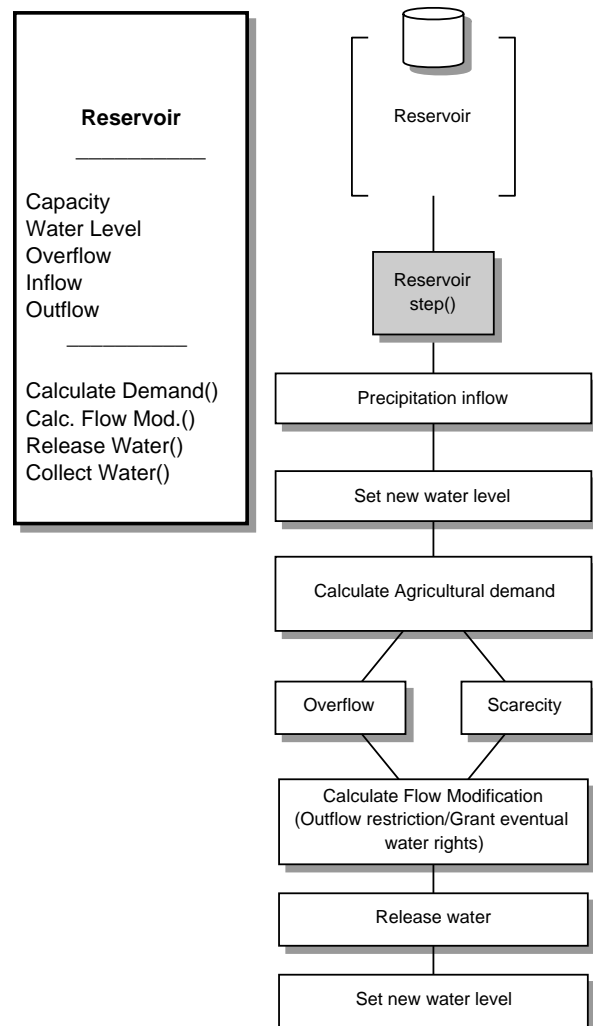


Figure 4-10: The Reservoir class parameters and functions.

amount of rainfall per year represents exactly the reservoir's capacity and thus the total water demand. Like this, a dynamic equilibrium is created. If there was no fluctuation, the water level of the reservoir would not change between the years, as inflow and outflow of the reservoir would be the same (for a discussion of this shortcoming see Chapter 5).

Table 4-2: Water use in Chile (DGA/MOP 2000).

Water use	Agriculture	Industry/Mining	Domestic	Other
	81 %	13,7 %	4.4 %	0,9 %

When precipitation inflow added to the current water level is higher than the reservoirs capacity, an *overflow* is produced. It is assumed in the model that the overflow can be used by the farmers to a certain degree. This depends on the capacity of the distribution system. The users of the model can control the capacity by setting the model parameter *overflowUse*. This value gives the amount of overflow water used for serving possible water rights. For example, if the overflow is 40000 m³ and the *overflowUse* parameter is set to 20 percent, 8000 m² can be used for serving possible water rights. As there was no data available for the amount of possible water rights per farmer, the overflow water was equally distributed among the farmers.

Depending on the amount of water rights currently demanded, and the current water level, the *outflow* out of the reservoir is calculated.

The *water level* is calculated at runtime and updated at every time step, taking into account precipitation *inflow* and *outflow* for agricultural demand.

4.5.4.2 Functions and Flow Dynamics

The **functions** and **flow dynamics** are shown on the right in Figure 4-10. First the reservoir receives a number of water from the precipitation class. The new water level is set. The class then calculates the demand for water based on the amount of water rights. The class then calculates how much water will be released. There are two rules:

1. If the water level would fall below half of the total agriculture demand *after* release of total agriculture demand, there will be a flow modification, a restriction of X percent to ensure that there is at least half of the minimum requirement in the reservoir⁴.
2. If there is an overflow, the flow modification will be negative and possible water rights (span.: 'derechos eventuales' are served. In the model this is realized simply by increasing the current water rights of every farmer by the calculated value in percent. This value is calculated by multiplying the overflow value (in percent) with the *overFlowUse* value, which is a Model parameter. It is the percentage of the overflow which can be used to serve possible water rights⁵.

The *flow modification* value lowers or raises the agents' amount of available water depending on the reservoir level. The purpose is to make sure that the reservoir does neither get totally empty nor leave overflow water the reservoir cannot hold unused. In this case the flow modification becomes negative, which results in an increase of water available for the farmers.

Based on the calculations of flow modification, water is released from the system, and the value is subtracted from the water level. The new water level is set.

4.5.5 Farmer class

4.5.5.1 Class parameters

The farmer Household in the Choapa model is assigned a certain amount of land in a parcel. In reality a farmer household might have more than one parcel. However, there were only a few cases found in the dataset in which the farmer household actually was assigned to more than one parcel. Therefore it was decided not

⁴ Code syntax: `if ((waterLevel - agricultureDemand) < agricultureDemand / 2)`

⁵ Code syntax: `if ((waterLevel - agricultureDemand) > capacity) ...`

to include this 1 : n relationship in the model, because the effort of coding this relationship would not pay off.

That way, every farmer household is assigned to one parcel only. There are 287 Farmer Households in total. Every parcel consists of at least one, but usually of several raster cells. The variable *arable land* was calculated by multiplying the number of cells of a parcel with the cell size per cell given in hectares (0.25 ha at the current resolution). Every cell was seen as arable; however, in a more mature version of the model, there might be cases to restrict this.

One of the objectives of the model is to simulate individual decision making, as there is only little data available for individual farmers. Therefore, data for a higher aggregation level was disaggregated to the individual farmer, mainly based on rules drawn out of literature reviews, personal interviews and observations. The shortcomings of this strategy are discussed in Chapter 5. The model accomplishes this on initialization of the Farmer household objects (see left branch of Figure 4-12, p. 55).

The variables *producer type*, *water efficiency* and *decision preference* was introduced in the model.

Response	Proactive	Reactive	Inaction
Policy/ institutional level	Investments in ground water re-charge; irrigation and flood protection etc.	Collective action and reciprocity in mitigating negative effects of change	Migration ignored as an adaptive response
Individual level	Diversification of livelihoods; investments in human and physical capital; new practices etc.	(Temporary) migration	Acceptance of negative effects

Table 4-3: A typology of adaptive responses at different intervention levels. (Adapted from **Paavola & Adger 2004**).

The two biggest producer groups of the Choapa Valley represented as *producer types* in the model are subsistence farmers and small commercial farmers. The vast majority are small producers (see Table 4-6). During agent initialization, this relation was simulated in relation to the amount of land the farmer household holds. A threshold value was calibrated in order to map the relation. A static variable called *producerTypeThreshold* was introduced; farmer households which possess less than 0.3 hectares were assigned the subsistence type, whereas farmers with more than 0.3 hectares were small producers. Thus, at the current resolution of the model (50 meters per cell), a farmer who has more than one cell was treated as small producer.

Differing on-site *water efficiency* is the result of the irrigation technique applied. The water efficiency is an important factor in arid zone agriculture, as the increase of a low water efficiency has a big impact on the availability of water resources and therefore on the productivity of the system. The overall water efficiency in the study area is very low: an annual flow of 10.9 m³/second supports 42.000 people and 17732 ha for agriculture (DGA 2004). This corresponds to a water efficiency of only 35.7 percent (see Table 4-4 and Table 4-5). The reason for this is probably the very traditional farming systems in the Choapa Region – there are mainly gravitational irrigation systems applied.

Table 4-4: Irrigation efficiency in the Coquimbo region based on DGA analysis. In: **Brown & Peña 2003.**

	Gross demand		Net demand		%
	Hm ³ /year	m ³ /s	Hm ³ /year	m ³ /s	
Elqui	164756	5.2	77291	2.9	46.9
Limarí	790847	25.1	274707	6.7	34.7
Choapa	318181	11.0	124314	3.9	35.7
Other basins	13513	0.4	4067	0.2	36.0
Total Region	1317920	41.8	481174	15.3	36.5

The same procedure used for the simulation of the *water efficiency* was chosen for assigning a spatial *decision preference* value for the farmer. This value determines the relative importance of the slope factor for decision making in relation to the

‘distance to water’ factor. For example, if the decision preference is set to 0.45, this means, that the slope factor is weighted with 40 percent and the ‘distance to water’ factor with 60 percent.

Table 4-5: Efficiency of irrigation techniques (**Brown & Peña 2003**)

Technology	Efficiency
Gravity (sheet, furrows, border, dikes and basins)	30 %
Major mechanical (sprinkler, microjet and microsprinkler)	70 %
Micro-irrigation (drip)	85 %

There was no data available on a farm basis for on-site water efficiency; however, based on personal interviews, it was assumed that subsistence farmers were using irrigation systems with a lower efficiency than small producers, who can count on somehow more sophisticated techniques for irrigation. Based on what has been said, a random efficiency value between 20 percent and 35 percent was assigned to the subsistence farmer, whereas a random value between 35 percent and 50 percent was assigned to the small producer type. That way, the overall *water efficiency* of the system is close to the observed value for the Choapa Valley, which is 35.7 percent (see Table 4-4).

The number of *water rights* was assigned to the farmer household based on data collected within the study of **Cabezas & Payacan 2005**.

The parameter *strategy* represents the action an agent takes according to his decision. Following a typology of adaptive responses by **Paavola & Adger 2004**, an Agent in the Choapa Model has three actions possibilities (see Table 4-3).

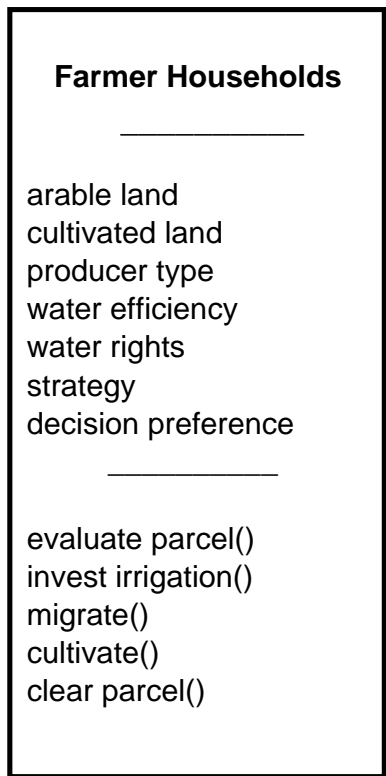


Figure 4-11: The farmer household class parameters and functions.

Firstly, an agent can be *proactive*, which means that he actively responds to the changing environment by implementing new practices, e.g. the diversification of livelihoods or the investment in human and physical capital. In the case of the Choapa Model, the agent invests in water saving technology in order to compensate for production loss as a result of decreasing water for agriculture.

The second concept, the *reactive strategy*, is coping with the situation by migration (see 4.5.5.5), avoiding the negative consequences of change.

The difference between the two terms is not obvious at first sight. To clarify this, one might think of the *proactive* response as ‘a positive way’ of reaction. Here, the farmer actively tries to improve his situation, within the given domain, whereas the *reactive* concept rather applies to a passive reaction that is leaving the domain. An alternative term may be ‘avoidance’.

The third strategy can be described as *inaction*; an acceptance of negative consequences as given facts.

Table 4-6 Agriculture census data for the Illapel census track (INE 1997).

	Subsistence	Small Com.	Medium Com.	Big Com.	Sum
Nr. of Exploitations	140	305	4	6	455
Irrigation agriculture (ha)	72.4	395.0	32.5	47.9	547.8
Dry agriculture (ha)	8.8	41.6	0.0	0.0	50.4
Total (ha)	81.2	436.6	32.5	67.9	618.2
Production (qqm)	673	3937	222	2214	7046
Return (qqm/ha)	8.3	9.0	6.8	32.6	11.4

%

Nr. of Exploitations	30.8	67.0	0.9	1.3	100.0
Irrigation agriculture (ha)	15.8	69.6	5.7	9.0	100.0
Dry agriculture (ha)	17.5	82.5	0.0	0.0	100.0
Total (ha)	13.1	70.6	5.3	11.0	100.0
Production (qqm)	9.6	55.9	3.2	31.4	100.0

4.5.5.2 The Farmer Class Actions

At every time step the farmer households' decision making is carried out within a special function, which itself calls other functions and so on. On the highest level there is the *farmer step* (see Figure 4-12). The function begins with an evaluation of the overall available water resources of the region, indirectly expressed by the reservoir level.

In a next step, a decision is made as to whether or not the farmer *adapts* his decision making. First, the agent decides if he wants to invest in irrigation technology (pro-active decision; see box 'invest...' in Figure 4-12). Depending on the available water resources, expressed as the reservoir's water level, an *investment probability* - a value between 0 and 1 is calculated based on a value function. If this probability is higher than a calculated random number between 0 and 1, then an investment will be made. (More details will be given in section 'Technology adaption' in Section 4.5.5.3). After this, the farmer has to update his *spatial preference*, because the farmer altered his on-farm technology level, and therefore has different preferences as to how and where to cultivate. Based on the newly updated spatial preferences, he re-evaluates his parcel (see box 're-evaluate parcel' in Figure 4-12) and cultivates his parcel (for details about the cultivate class see Section 4.5.5.6).

If the farmer decides *not* to invest, he might decide to temporarily migrate out of the system (reactive decision; see box 'temporary migration' in Figure 4-12). The *migration probability* is calculated in a similar way as the investment probability. Section 4.5.5.5 gives a detailed description of migration dynamics. If the farmer migrates, he clears his parcel.

If the calculated random numbers are lower than the calculated probabilities of adaption, then no adaption is realized. Then the farmer simply cultivates his parcel (see box 'cultivate' in Figure 4-12; see Section 4.5.5.6).

Independent of the described processes in this section, a farmer, who has temporarily migrated, might want to return to continue his agricultural activity (see box 'immigration' in Figure 4-12).

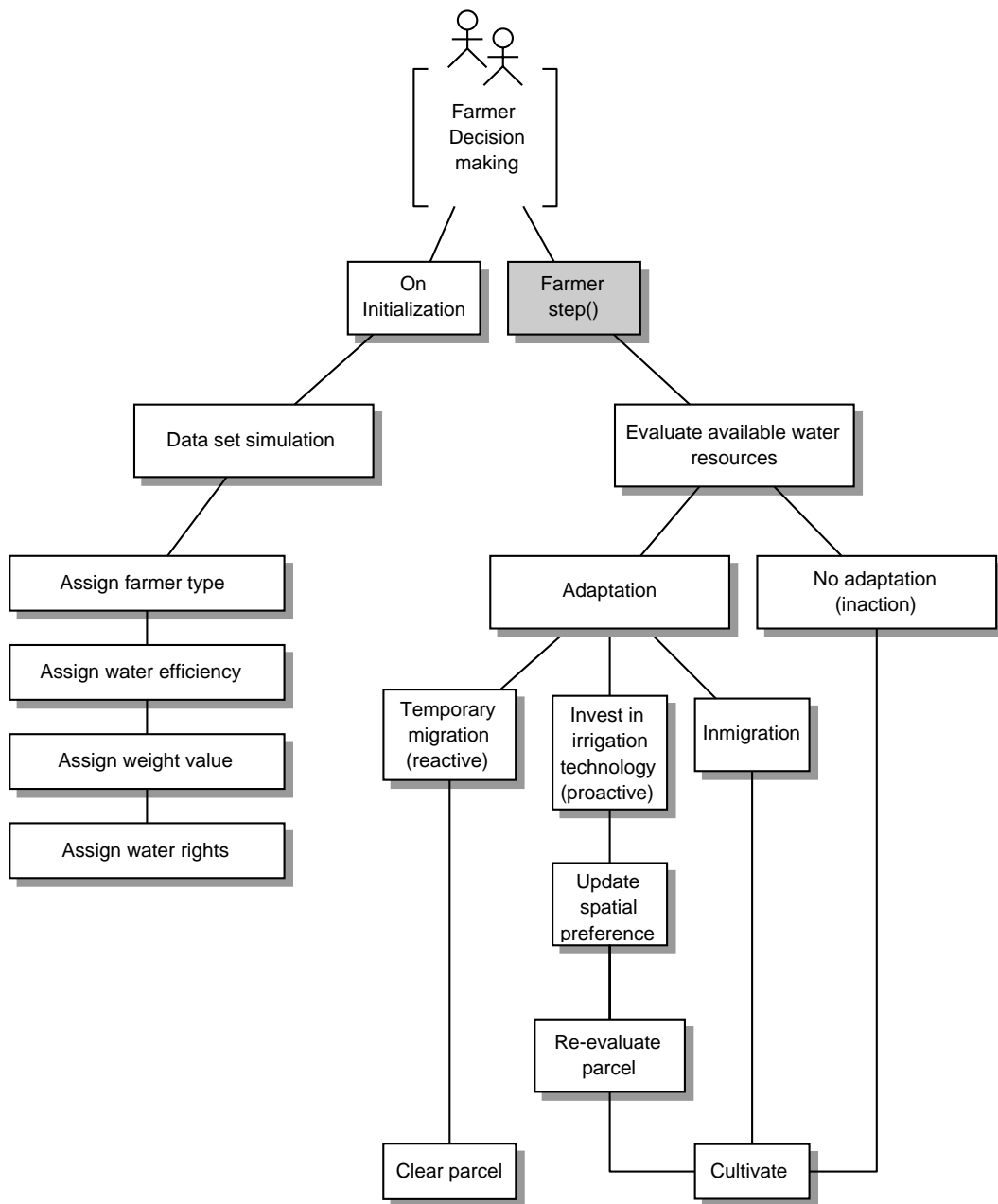


Figure 4-12: The farmer class flow diagram. Left branch: Agent Initialization. Right branch: farmer's actions executed at each time step during operation.

4.5.5.3 Technology Adaptation

Technology adaption of a farmer household is based on an *adaption probability* calculated by a value function (see Figure 4-14). The given polynomial function can express a slightly more complex behaviour than a linear function.

In the model, technology adaption is related to the availability of water resources. Generally, it is assumed that the diffusion process is rather slow when enough water resources are available. For example, this might be the case when the reservoir level constantly varies between 70 to 100 %. Nevertheless, the diffusion process is assumed to intensify if the water level drops, because the farmer realizes that his production resources are limited, and as a consequence his willingness to invest in water saving technology rises. However, if the water level is *very* low, the farmer's willingness to invest decreases, because in the face of a water crisis, he rather waits until the supply situation has improved than spend higher amounts of money with an uncertain benefit.

Every time step, every farmer 'thinks' about investing in irrigation infrastructure. Technically, the function in Figure 4-14 is used to transform the reservoir level into a probability threshold value. Then a random number (0 to 1) is calculated. If the random number is below that threshold, then the farmer adapts his technology level and the parameter *technology level* will increase. As well as the adaption probability, the adaption **intensity** (how much to invest) is based on a pseudo-random number. However, the user of the model can control the intensity by providing the model with a value for the model parameter *technologyAdaptionPercent*. This parameter limits the increase to a certain value. For example, if *technologyAdaptionPercent* is 30 percent, then the increase of the current value will be a random number between zero and 30 percent.

4.5.5.4 Spatial Decision Making

The farmer evaluates the quality of his parcel by several criteria. These criteria can vary over space, which results in a local heterogeneity within his parcel. To spatially evaluate his parcel, the farmer has to evaluate his parcel at several locations, to find out where the relatively 'best' location is. In order to assess this problem with a consistent decision making framework, the Choapa model uses a module for micro-level multi-criteria decision making adopted from the classical 'spatial decision support system approach', using weighted sums as an aggregation rule (Malczewski 1999; on the theory see Section 2.5 and Chapter 3). There are two criteria evaluated: slope and distance to water. In fact, these factors are very often

used in decision making and proved to be effective. However, it is relatively easy to add more factors to the two existing ones at a later stage of modelling. For example, in farm management theory, the internal transport cost, the distance from the farmers homestead to his parcel, can be a limiting factor (Berger 2000). Local heterogeneity can also be a result of neighbouring land uses (Parker 2001).

This intermediate result is multiplied with the constraint map, which sets all constrained raster cells to zero, therefore resulting in a suitability value of zero. The mentioned operations result in a 'suitability' map, as weighted sum of the two factor maps (see Figure 4-28, p. 74). As the input raster datasets were standardized to values between 0 and 255, the resulting raster has a maximum of 255. The higher the value, the higher the suitability for the farmer. Red values represent very unsuitable locations, whereas green locations are relatively better apt.

The model is embedded in every single agent, which permits having individual sets of decision making preferences. This in turn has an effect on the weighting of the two decision factors. A farmer applying modern farming and irrigation technology in his vineyard can compensate for sub-optimal soil fertility or steep slopes. Therefore the weight for the factor *slope* is lower than for the factor *distance to water*. However, a traditional 'campesino'-farmer, producing crop with traditional irrigation techniques is much more concerned about soil fertility and slope conditions in his parcel. This type of farmer would weight the slope factor higher.

The model assumes that if the farmer invests in irrigation infrastructure he is also going to change his decision preference. Due to the lack of empirical data, there was a simple relation modelled between the technology adaption and the decision preference: if the farmer increases technology level by X percent, he will at the same time lower his preference for the slope factor by X percent.

As a result, the suitability for cultivating does not only change in time for the whole study area, but also changes locally on the parcels. Figure 4-13 gives an example for changing decision preferences and the resulting suitability maps at different time steps.

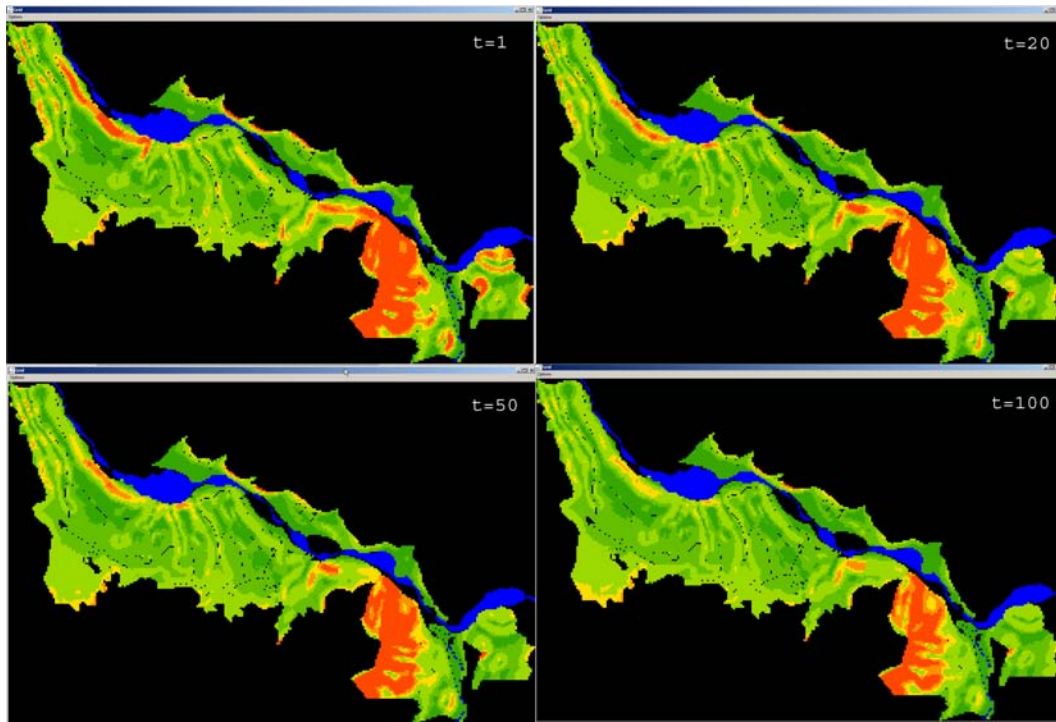


Figure 4-13: Changing suitability for agriculture is a result of intrinsic adaptation of the farmers to improvement of their technology and irrigation infrastructure (t= years).

As can be seen in this figure there is no uniform change, which applies to the whole region. Rather, suitability changes in a locally disaggregated way, and is taking place asynchronously on the parcels.

4.5.5.5 Migration Dynamics

A farmer starts to think about alternatives to his agricultural activity, because a decreasing water supply makes it more and more difficult to sustain his income. The farmers then temporarily stop their agricultural activity in order to earn money in other parts of the region or country. They usually return when the conditions in the home region permit this, that is when there are enough water resources for stable agricultural activity.

The user of the model can control the emigration by providing the model with a threshold below which the emigration process starts. The *intensity* of the migration is calculated by help of a value function (see Figure 4-14). If the reservoir

level is below the threshold, the reservoir level value is passed to the function, which returns a probability value between 0 and 1. The higher this value is, the higher is the probability of the farmer to temporarily migrate out of the region.

At every time step the farmer then ‘thinks’ about a temporary migration. The ‘willingness of emigration’ of the farmer is calculated by a random uniform function, which returns a value between 0 and 1. If his ‘willingness’ to leave is higher than the returned value of the migration function, the farmer will stop agriculture activity and leaves the region for work in another field.

The contrary happens if the water reservoir shows optimum capacity. The more water the reservoir holds, the higher the probability of a farmer to return to his parcel to start agricultural activity again.

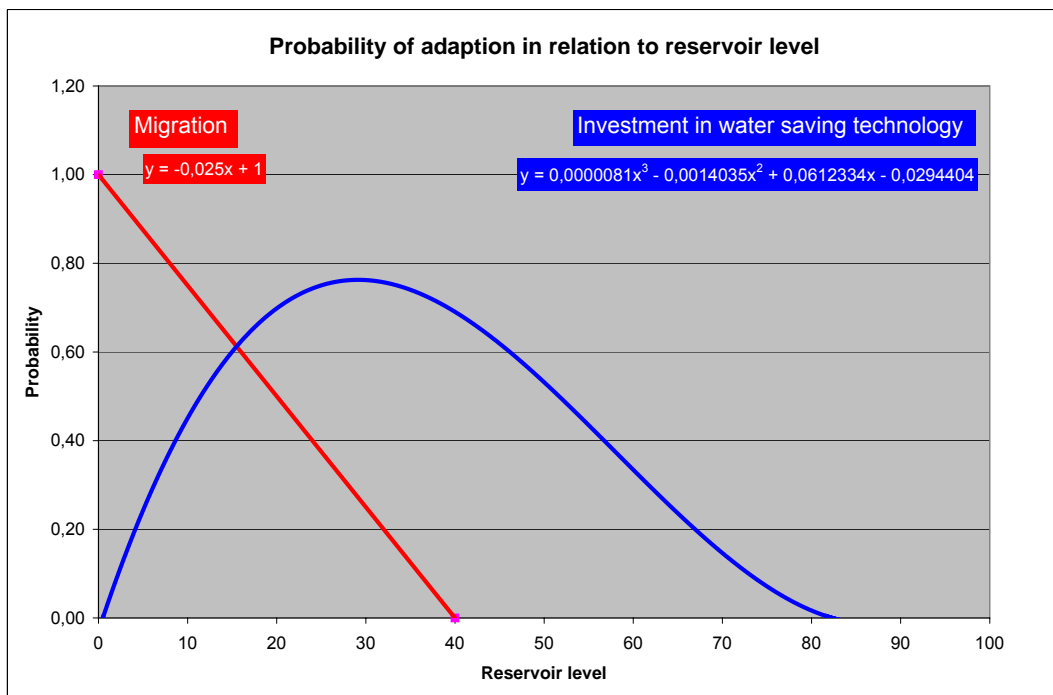


Figure 4-14: Value functions for transferring the reservoir level value to probabilities of migration and probabilities of diversification actions as part of the decision making model.

4.5.5.6 Cultivating

This section explains the spatial decision making of the farmer households. It refers to the box 'cultivate' in Figure 4-14.

Every time step/year, the agent calculates how much he can plant according to the number of water rights he possesses, the water efficiency and the flow modification of the reservoir manager⁶. Then he compares it to the space cultivated to calculate the change he has to make⁷. The value is passed to the function 'cultivate'. Based on the current cell size the function calculates how many cells the farmer has to clear, or how many cells he can cultivate in addition. The least or best suitable location is chosen based on suitability. Suitability is calculated according to the spatial decision model of the agents. The function then iterates through all cell of the farmers parcel. If the farmer has to clear a cell the least suitable of those currently cultivated are removed. If the farmer is able to cultivate more, then a cell with the maximum suitability of those currently not cultivated is chosen for cultivation. This is done until the number of cells which have to be added or removed to the current, is matched.

4.5.6 Environment Class

This section portrays the components of the agents' environment. The environment of the Choapa Model consists of different raster layers, with identical cell size and extent, representing

- continuous attributes for decision making, like 'slope' or 'distance to water'
- discrete spatial entities, for example the river bed, or the partition of land into parcels

The creation of the raster datasets by using Geographical Information Systems will be explained. Then the initialization process within the model, including data

⁶ code syntax: $\text{supportedCultivateableLand} = (\text{wR} * \text{wE}) - ((\text{wR} * \text{wE}) * \text{fR} / 100)$; with wR= total amount of water rights, wE=water efficiency and fR=flow restriction

⁷ code syntax: $\text{cultivationChange} = \text{supportedCultivateableLand} - \text{cultivatedLand}$

import and Agent initialization is outlined. This refers to the left branch of Figure 4-15. After that follows a short outline of the analysis functions of the class during model runtime (right in Figure 4-15).

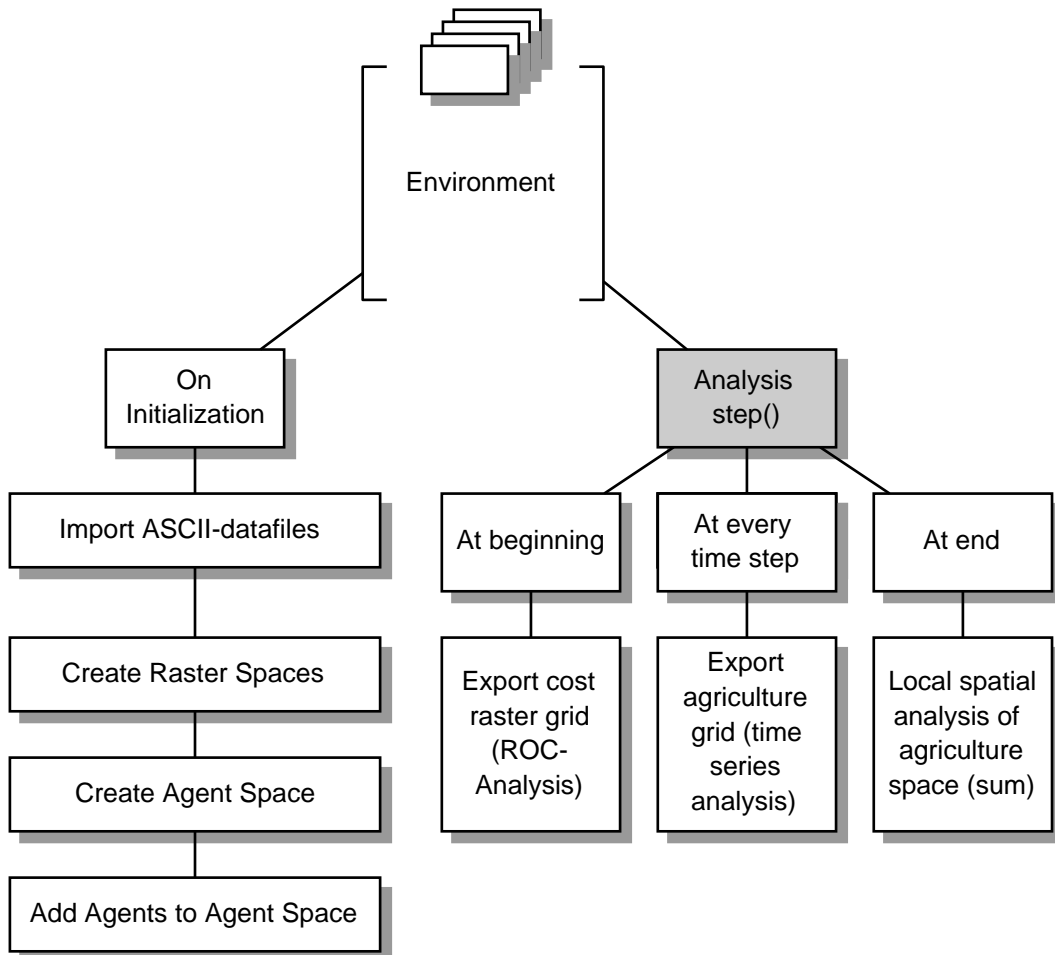


Figure 4-15: Basic action flow diagram of the environment class.

4.5.6.1 Parcel Dataset Generation Model

The parcel geometry shapefile produced by **Cabezas & Payacan 2005** was checked for errors to have a topological correct dataset with no overlaps and doubles. The number of water rights was available for each parcel.

Within the model builder of ArcGis 9.0 (**ESRI 2005**), the shapefile was converted into a raster dataset with a cell resolution of 50 meters (see Figure 4-16). After this a reclassification procedure was executed in order to remap NoData values to zeros, due to problems while data import. Then the raster dataset was converted into an ASCII-based raster dataset. This file format was used because the Repast libraries provide a class to import ESRI-ASCII raster datasets conveniently. The raster dataset holds an identifier value as information, in order to relate the agents to their parcels.

The second dataset generated from the Shapefile is a raster dataset, which holds information about the number of water rights per parcel. There is no spatial variation within the parcel. This raster layer is used to assign water rights during agent initialization.

Another three raster datasets were created; however, they are used only as a 'dummy' raster dataset, as they do not contain any information besides zero-values:

- A suitability grid which is filled later, during model operation, with the suitability values based on the weighted overlay operations
- An agent grid, with the function to provide a layer for the agents home-stead.
- A grid for agriculture information, which holds information whether a cell is cultivated or not, therefore it has a possible value of only zero and one.

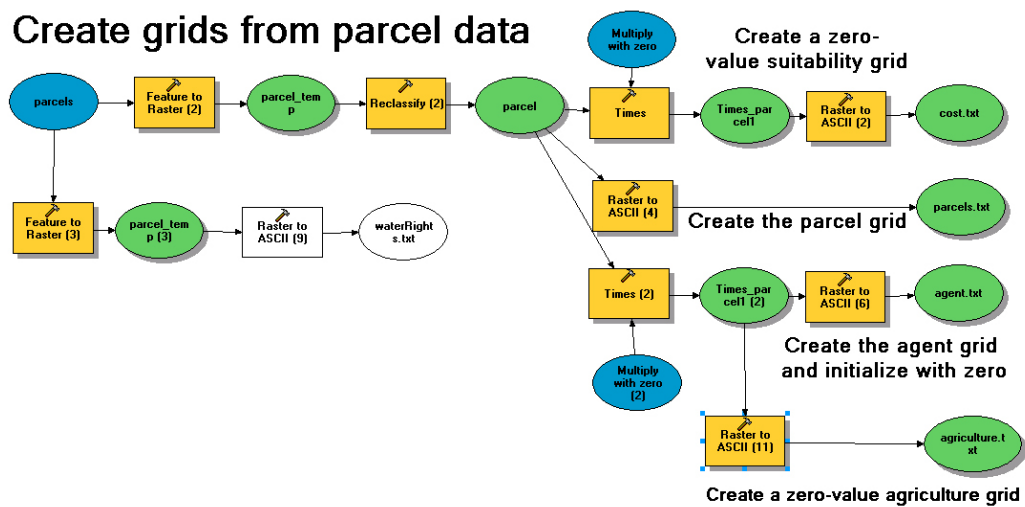


Figure 4-16: Input data generation from parcel data.

4.5.6.2 Slope Factor Map Generation

Original Data is drawn from a database of Cabezas & Payacan 2005, which consists of contour lines and spot heights. An ArcInfo module called ‘TopoToRaster’ was used to interpolate an elevation surface (see Figure 4-17). ‘TopoToRaster’ is an interpolation method designed for the creation of hydrologically correct digital elevation models, based upon the ANUDEM program developed by Hutchinson 1988. The advantage in comparison to other methods is that it permits to use a variety of input data: spot heights, contour lines, river networks, lakes etc.

After the generation of the digital elevation model, a slope model was generated using the ‘Slope’-Module from the ArcToolbox. The generated dataset was exported as an ASCII-Textfile. After this, the slope dataset had to be standardized. A standardization based on a fuzzy set was used (see Section 3.2.3). This was considered useful to enable a more realistic expression of the relation between agricultural suitability and slope. For convenience, the procedure was outsourced to IDRISI, because the software provides a good interface for fuzzy dataset modeling and criteria map standardization based on these sets (see Figure 4-18).

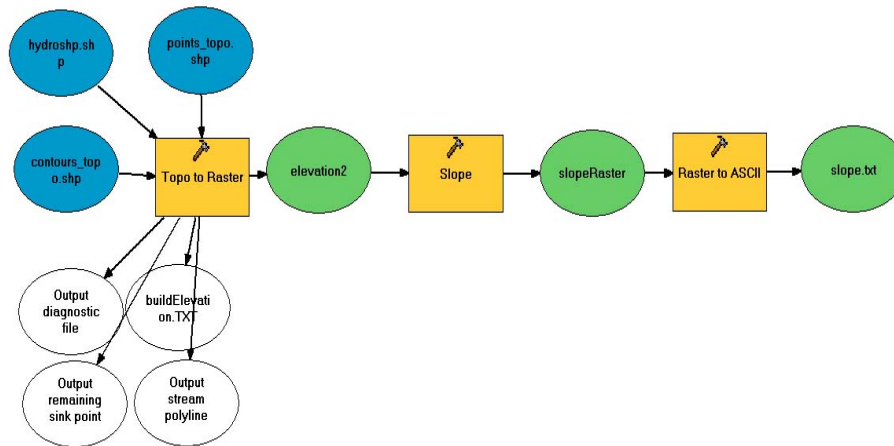


Figure 4-17: Input data generation from GIS data. ArcGis model builder. Slope data generated from contour lines.

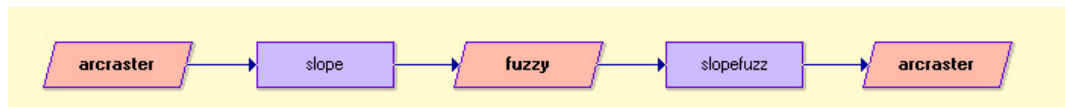


Figure 4-18: Slope data from ArcGis model is fuzzified with IDRISI software.

A monocronical decreasing, and ‘J-shaped’ membership function shape was chosen (see Figure 4-19). It was assumed that a slope value between 0 and 5 degree had the highest utility. Slope values between 5 and 15 degrees were assigned lower values, sigmoidally declining until zero, and slopes higher than 15 degrees, were found inadequate for agriculture, therefore the utility for slopes higher than 15 degrees were set to zero.

Figure 4-20 shows the result of the fuzzification process. Values range from 0 to 255. Lower values with yellow tones equal a low suitability, whereas higher values with shades of green and darker green signify good suitability for agricultural activity.

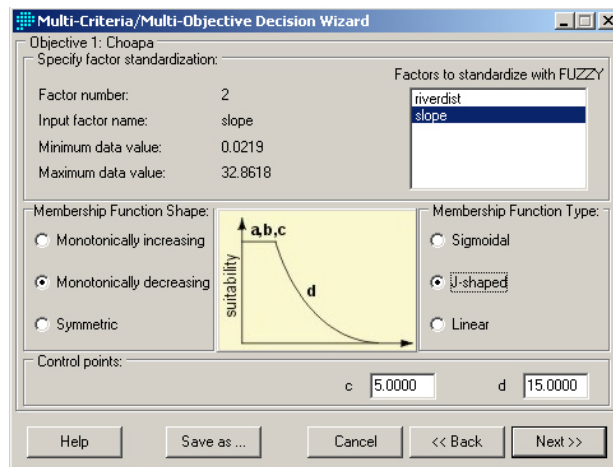


Figure 4-19: Parameter set for fuzzification with IDRISI software.

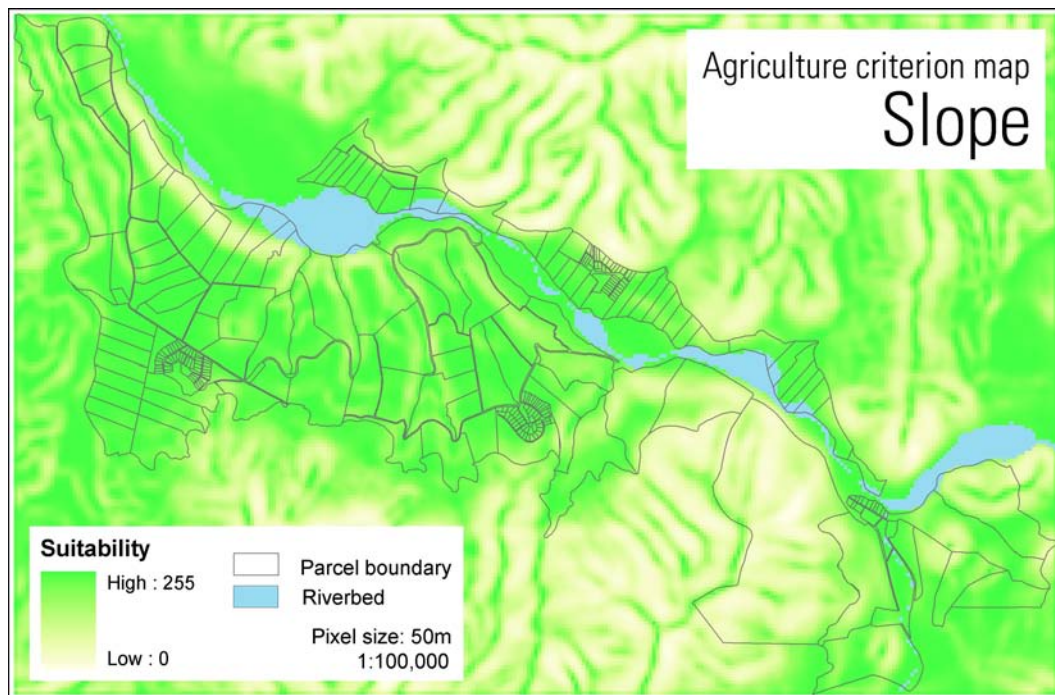


Figure 4-20: Result of fuzzification procedure with the above given parameters.

4.5.6.3 River Distance Factor Map Generation

The procedure for generating the second criterion map is similar to creating the slope criterion map: the first step is to convert the riverbed polygon shapefile to a raster dataset (see Figure 4-21, lower branch). The raster dataset is reclassified in order to eliminate 'NoData' values and to create a binary factor map, which represents a value of one for the riverbed, and zero for the rest of the space. The raster dataset is exported and is again passed to the IDRISI software. Within the IDRISI package, a distance calculation is executed (see Figure 4-22). The riverbed cells are considered to be the source cells for the distance calculation. For each cell, the distance is calculated to each of the source cells. The shortest distance to the source is determined and the value is assigned to the cell location on the output raster. The next step is to standardize the criterion map in order to match the value range to the slope criterion map. As well as for the slope factor map, the standardization of the river distance criterion map is based on a fuzzy set. A symmetric, sigmoidal membership function is chosen (see Figure 4-23). Generally the suitability for irrigation agriculture production decreases with increasing distance to the water source, especially when the irrigation system is based on gravity. However, the membership function indicates that between 0 and 30 meters distance to the riverbed, the utility increases from zero to the maximum. This is based on the fact that within this distance, the anastomosing river occasionally leaves its bed which leads to short flooding events. Therefore a negative effect is assumed within this range. It might be worth noting that at the current resolution of 50 meters, this does not have a high impact on the output. Between 30 and 200 meters, the distance to water reaches its maximum. At a distance of 200 meters and higher, the utility decreases with increasing distance.

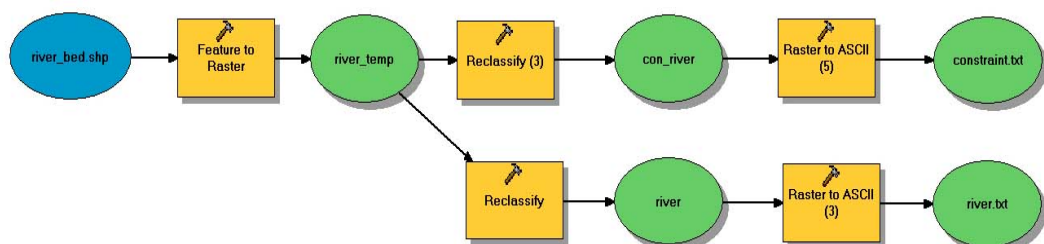


Figure 4-21: Input data generation from GIS data. ArcGIS model builder.

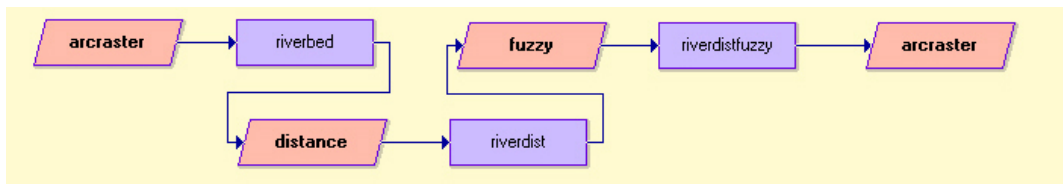


Figure 4-22: Distance calculation and fuzzification of river data.

The upper branch of the model in Figure 4-21 shows the creation of a constraint map. Based on the riverbed raster dataset a reclassification procedure assigns all cells to 0, where the riverbed runs, and the rest of the cells to 1. If this raster dataset is multiplied to any other raster, the resulting dataset keeps its values, where the constraint raster holds ‘ones’. The resulting raster dataset shows ‘zeros’, where the constraint raster set was assigned zeros as well, no matter what input data it hosted. In the domain of the farmer households’ decision making model, this procedure can be described as a post-elimination of decision alternatives.

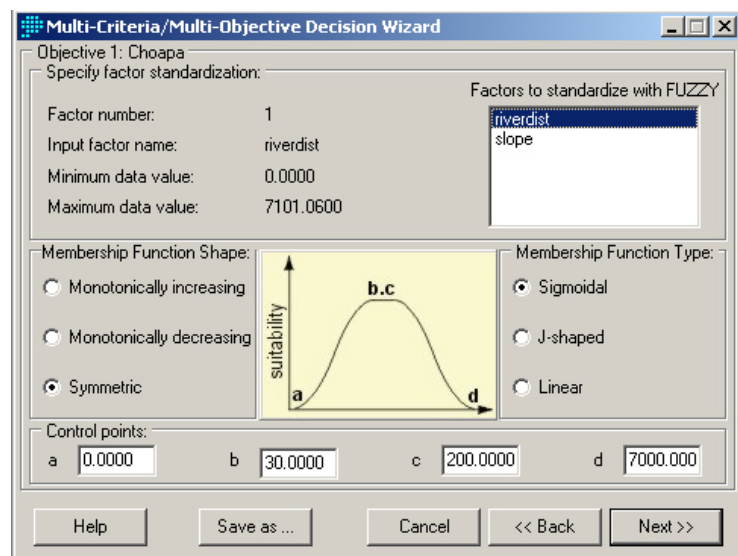


Figure 4-23: Parameter set for fuzzification with IDRISI software.

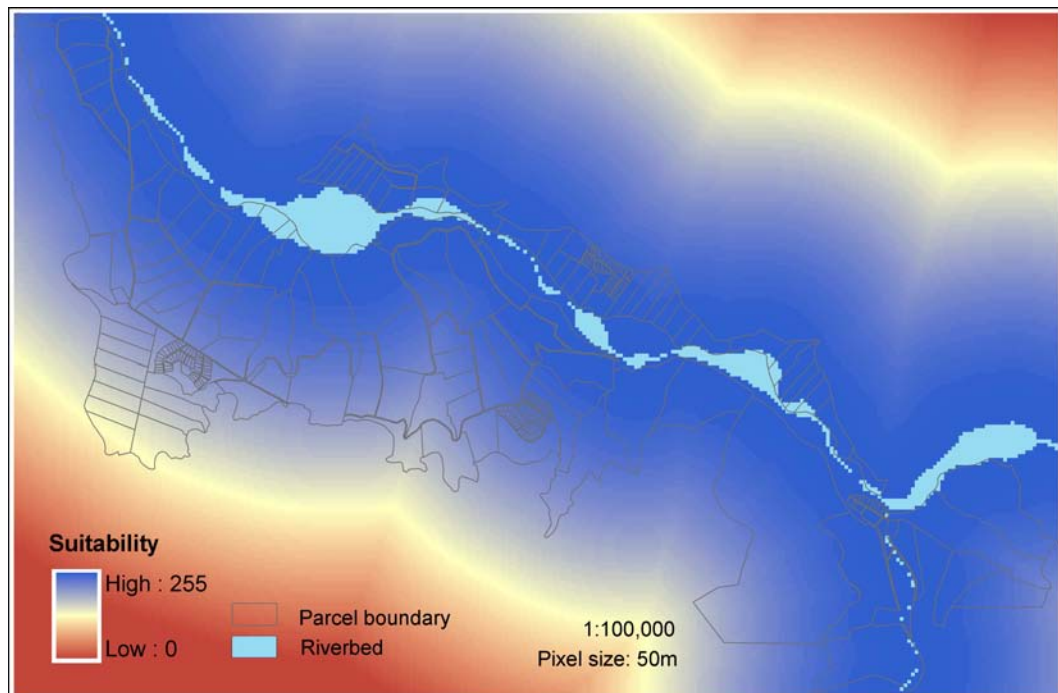


Figure 4-24: Parameter set for fuzzification with IDRISI software. Decreasing suitability from blue to red.

4.5.7 Conclusion

The previous section described and explained the model and its dynamics in detail. References to Chapter 3 were made in order to relate it to the underlying theory. At the same time, an overview over the technical qualities of the model was given. Then the model was classified, based on a typology of **Hare & Deadman 2004**. The possible roles of the model were outlined and the main system dynamics were explained. The classes' properties and functions, and the dynamics they add to the simulation were presented.

The following sections present the capabilities of the model 'in the wild', by running two simulations based on different parameter settings.

4.6 Agriculture Assessment

As an example for the capabilities of the model, an experimental agriculture assessment was carried out. The underlying question of interest is how the agriculture irrigation system would evolve quantitatively and spatially if the precipitation decreased in the next decades. Two scenarios are defined and assessed by the model.

4.6.1 Scenario Development

Scenario 1:

The parameter settings for the ‘base scenario’ are given in Figure 4-25. It is assumed that no climate change affects the region in the following decades, therefore assuming a mean annual precipitation of 215 mm. The climate variability was simulated as standard deviation from the mean value, based on the analysis of the times series (DGA 2004, CRIA 2005).

The reservoir capacity is set to 15000000 m³ of water.

Scenario 2:

The parameters of the second scenario - the ‘IPCC-Scenario’ - are defined according to the findings of the Intergovernmental Panel on Climate Change (IPCC). The IPCC was established by UNEP and WMO to assess scientific and technical research in the field of climate change (see IPCC 2001). Gen-

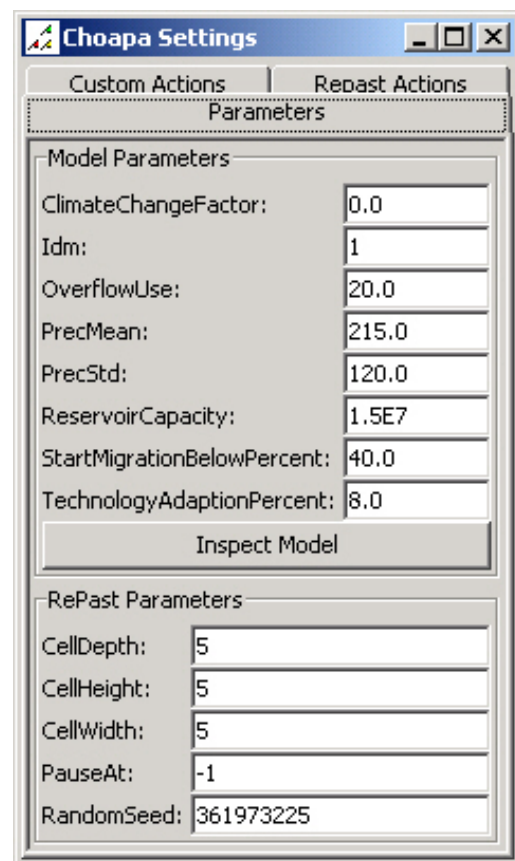


Figure 4-25: Parameter set for the ‘Base scenario’.

eral conclusions for the Latin American region, and especially for the study area, the Chilean 'Norte Chico', are drawn. In the report of the Working Group II 'Impacts, Adaptation and Vulnerability', it is stated that

"(...) agriculture remains a key sector in the regional economy because it employs 30–40% of the economically active population. It also is very important for the food security of the poorest sectors of the population. Subsistence farming could be severely threatened in some parts of Latin America (e.g., north-eastern Brazil). (...) Evidence is established but incomplete that climate change would reduce silvicultural yields because water often limits growth during the dry season, which is expected to become longer and more intense in many parts of Latin America." (IPCC 2001).

Then, in a regional report (IPCC 1998), it is argued that water is a critical resource for the development of the Latin American region. **Downing 1992** specifies that

"(t)he balance of irrigation requirements and water resources in northern Chile is already critical and drought episodes endanger production. A warmer environment entails increased irrigation needs for grapes and possibly dramatic shifts in river basin hydrology. Climate change, particularly if drought risk increases, accelerates the point at which economic expansion becomes constrained by water resources for agriculture" (**Downing 1992**).

Again in the regional report, a decreased yield for the crops mentioned above is projected, "even when the direct effects of CO₂ fertilization and implementation of moderate adaptation measures at the farm level are considered" (IPCC 1998).

Within the IPCC regional study **Downing 1992** projects an increase in Maize and Potato production; however, the more important 'grapes production' will probably decrease. The given projections are relative to the 1990's condition, based on a precipitation decrease of 25-30 percent by 2020 and a temperature increase of 2-3 percent by the same year.

These assumptions could be realistic if the current trend in precipitation change continues. **Ferrando 2003** calculated the precipitation change between 1921 and

1980 of three cities in the Norte Chico region. All three showed a strong precipitation decline; 28.6, 36.0 and 45.3 percent.

Based on the findings of **Downing 1992**, **Ferrando 2003** and **IPCC 2001**, the precipitation change parameter in the Choapa model was set to -0.7 percent, which corresponds to a decline of about 40 percent in 58 years. The first 42 years are based on real world data, and then a random uniform function calculates further precipitation values based on the analysis of the given series (see Section 4.5.3). As the total time period is 100 years, the precipitation decrease caused by the introduced *climate change parameter* approximately accounts for a total precipitation decrease of 40 percent in the remaining 58 years, which is a relatively moderate decrease compared to the calculations of **Downing 1992**, **Ferrando 2003** and **IPCC 2001**.

4.6.2 Simulation Output

A number of results were produced based on the two scenarios created. In Figure 4-27 the simulation outcome is shown as a 100 years sequence, separated in four charts. The charts contain one or two of the most important parameters of the model. Each chart presents the results for the two scenarios together in order to compare them to each other. The parameters analysed are:

- **precipitation** values in mm/year
- **reservoir level** in litres * 10^7
- the amount of **cultivated land** in hectares
- number of **farmer households** (percent)
- average **water efficiency** (percent)

For an interpretation of these results see Chapter 5.

Furthermore, a spatio-temporal analysis was conducted (Figure 4-28, Figure 4-29 & Figure 4-31). Figure 4-28 shows the sum of the spatial distribution of the agricultural activity for the first scenario, the base scenario. It was calculated by a local analysis function (local sum). The calculation was carried out within the Agent-Based Model. The resulting raster dataset was then exported to a format readable by ArcGis software and imported for further analysis. The minimum cell value of

the raster dataset is 0 and the maximum value is 100. For example, a cell value of 100 signifies that the cell was cultivated in every year, whereas a value of 90 indicates, that only in 90 of the 100 years sequence, the cell was under cultivation. The same logic applies to Figure 4-29, in which the results for the second scenario, the IPCC-scenario, is presented.

The map in Figure 4-31 is a synthesis of two raster datasets. The raster of Figure 4-28 was subtracted from the raster of Figure 4-29 in order to analyse the difference between the calculated sets. Negative values, with redish colours indicate a calculated decrease of agriculture activity for the IPCC-scenario in contrast to the base scenario. Greens and positive cell values indicate a calculated increase of agriculture activity in the respective cell for the IPCC scenario compared to the base scenario. An interpretation of the results of the spatial analysis is given in Section 4.6.3.2.

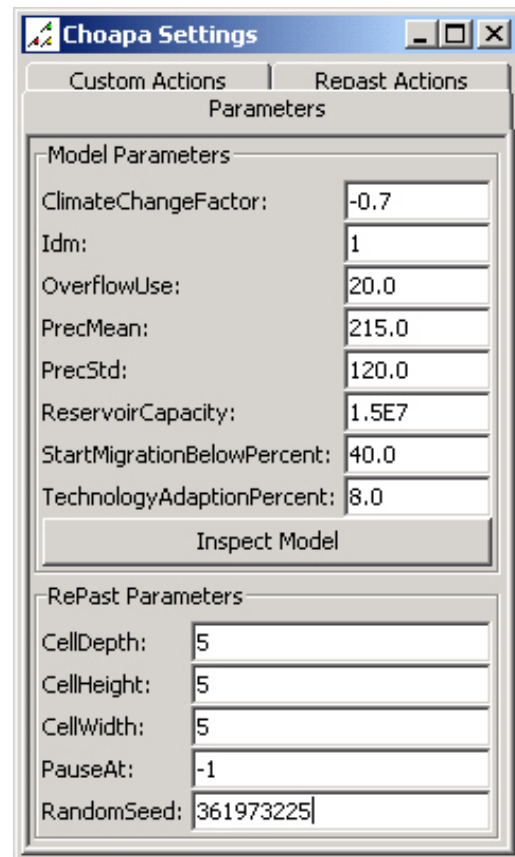


Figure 4-26: Parameter set of the 'IPCC scenario'.

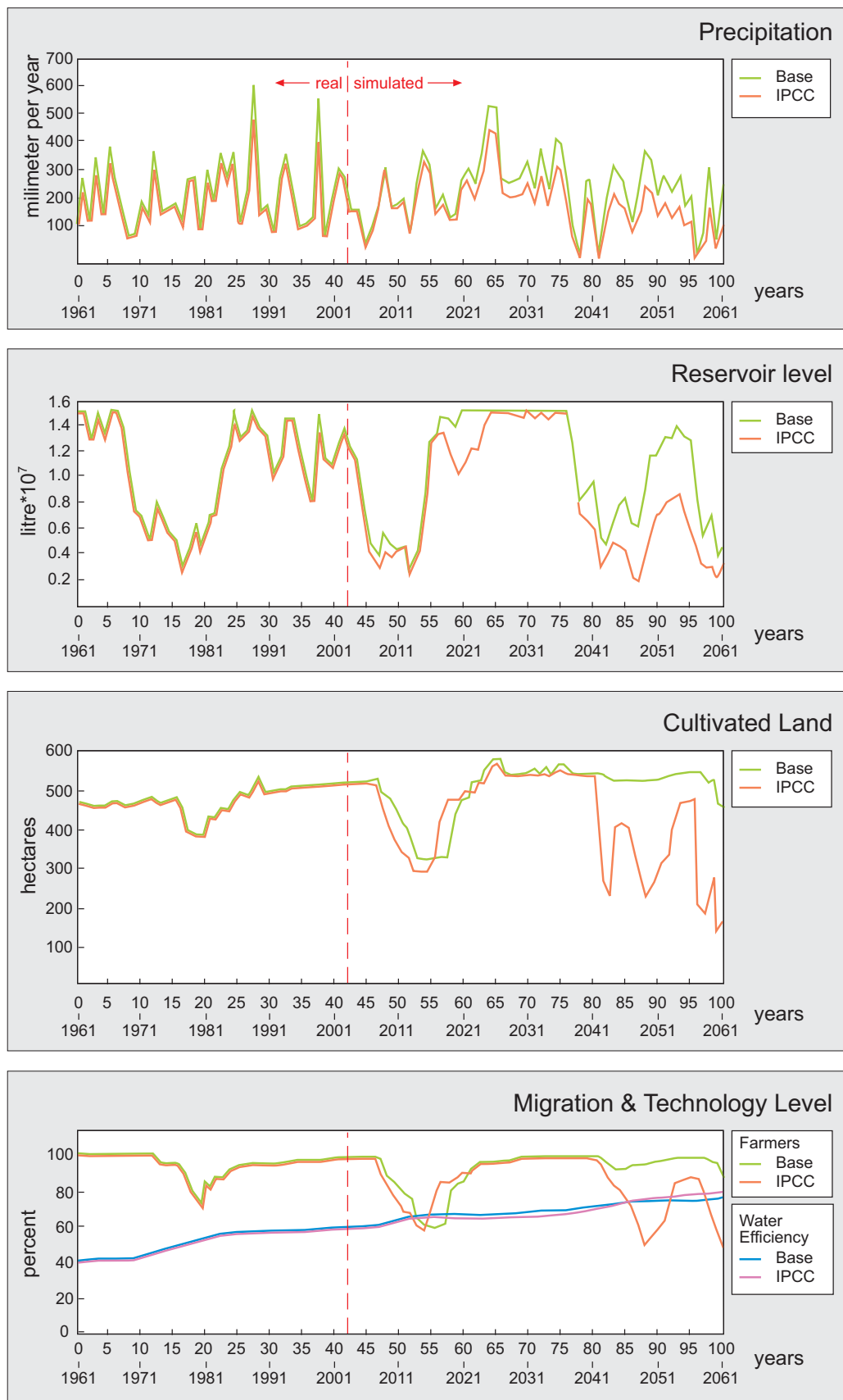


Figure 4-27: Simulation output of the 'Base' and the 'IPCC' scenario.

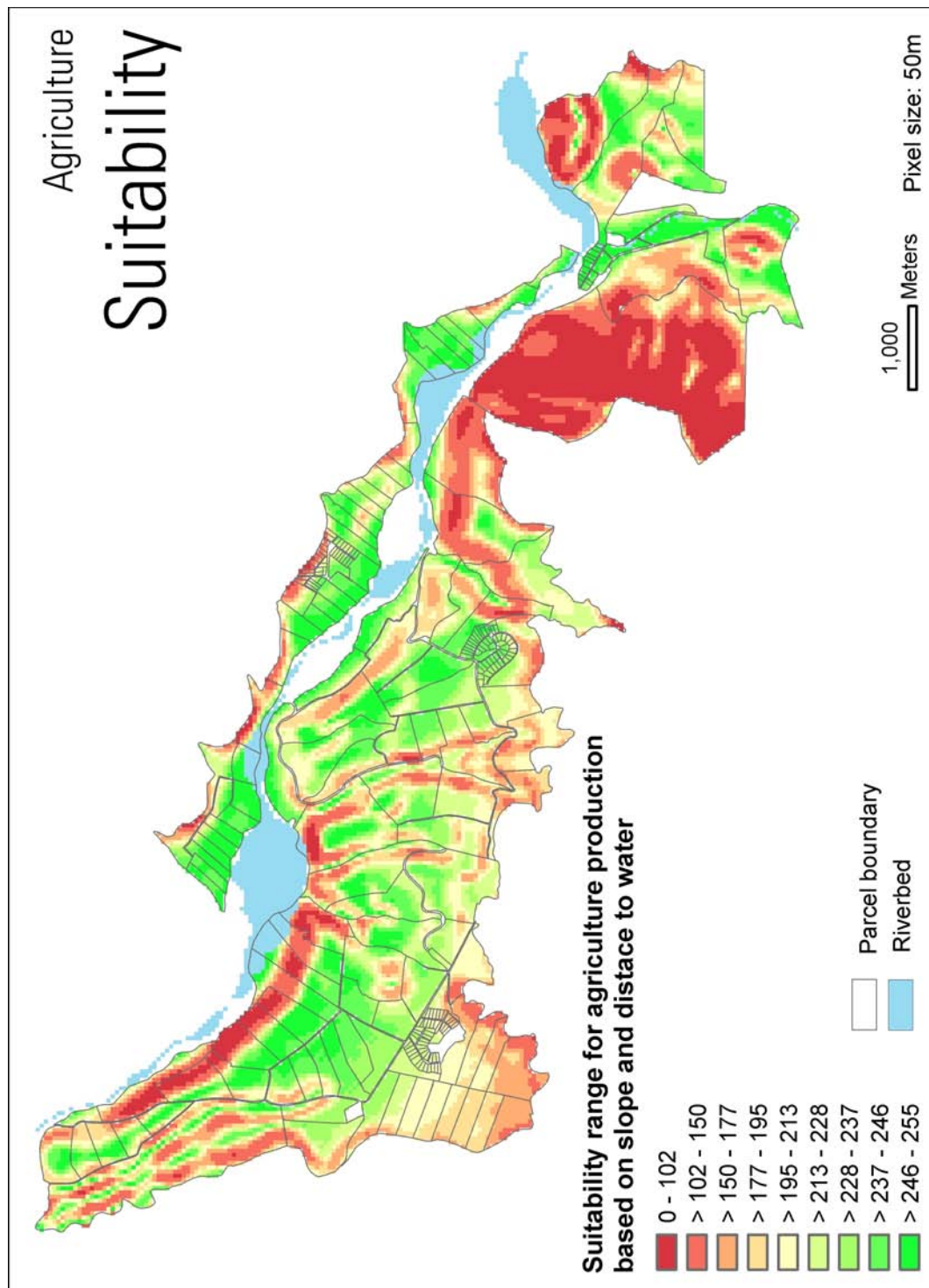


Figure 4-28: Suitability map for cultivation based on slope and distance to water.

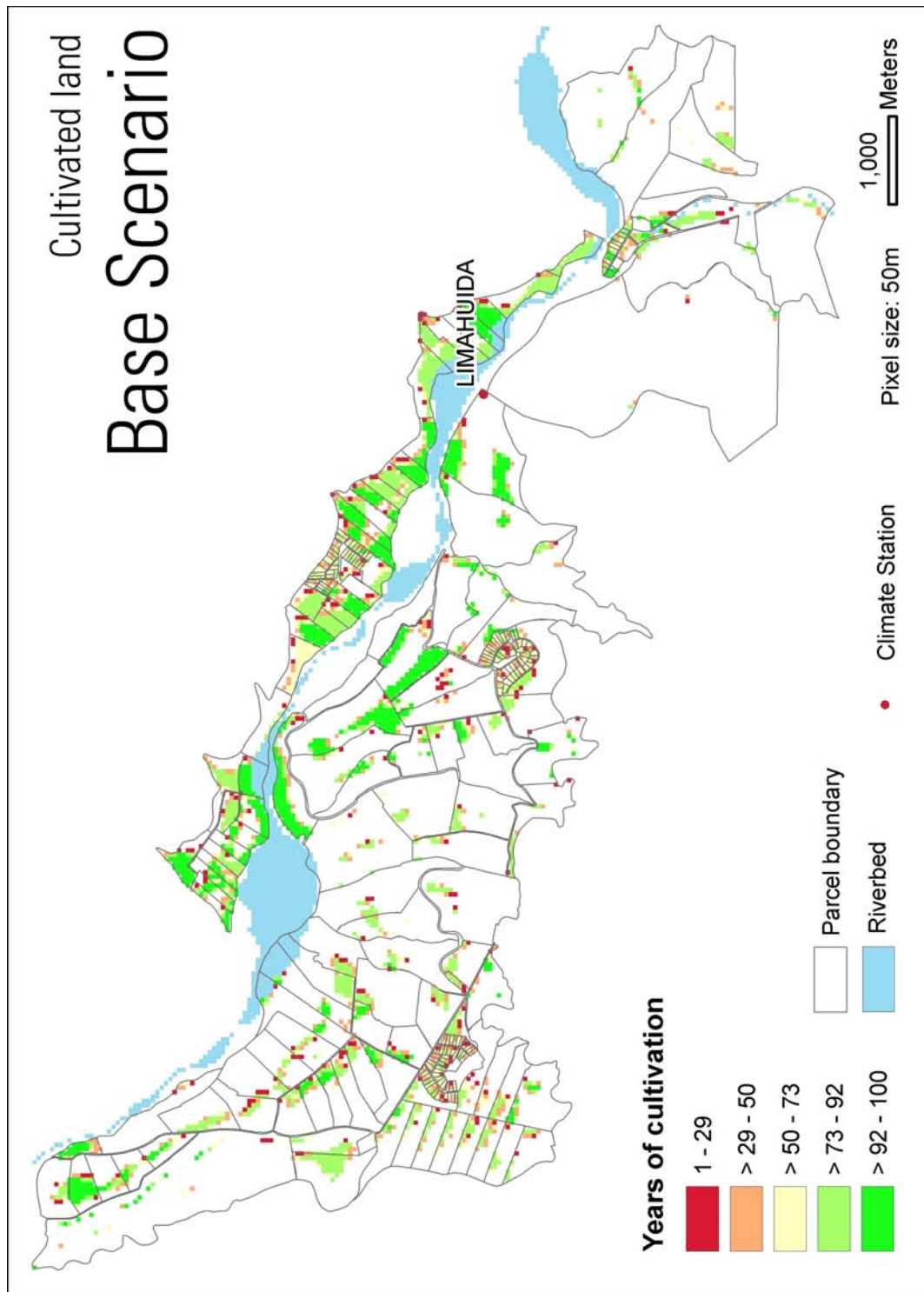


Figure 4-29: Local analysis of agriculture time sequence. 'Base' Scenario.

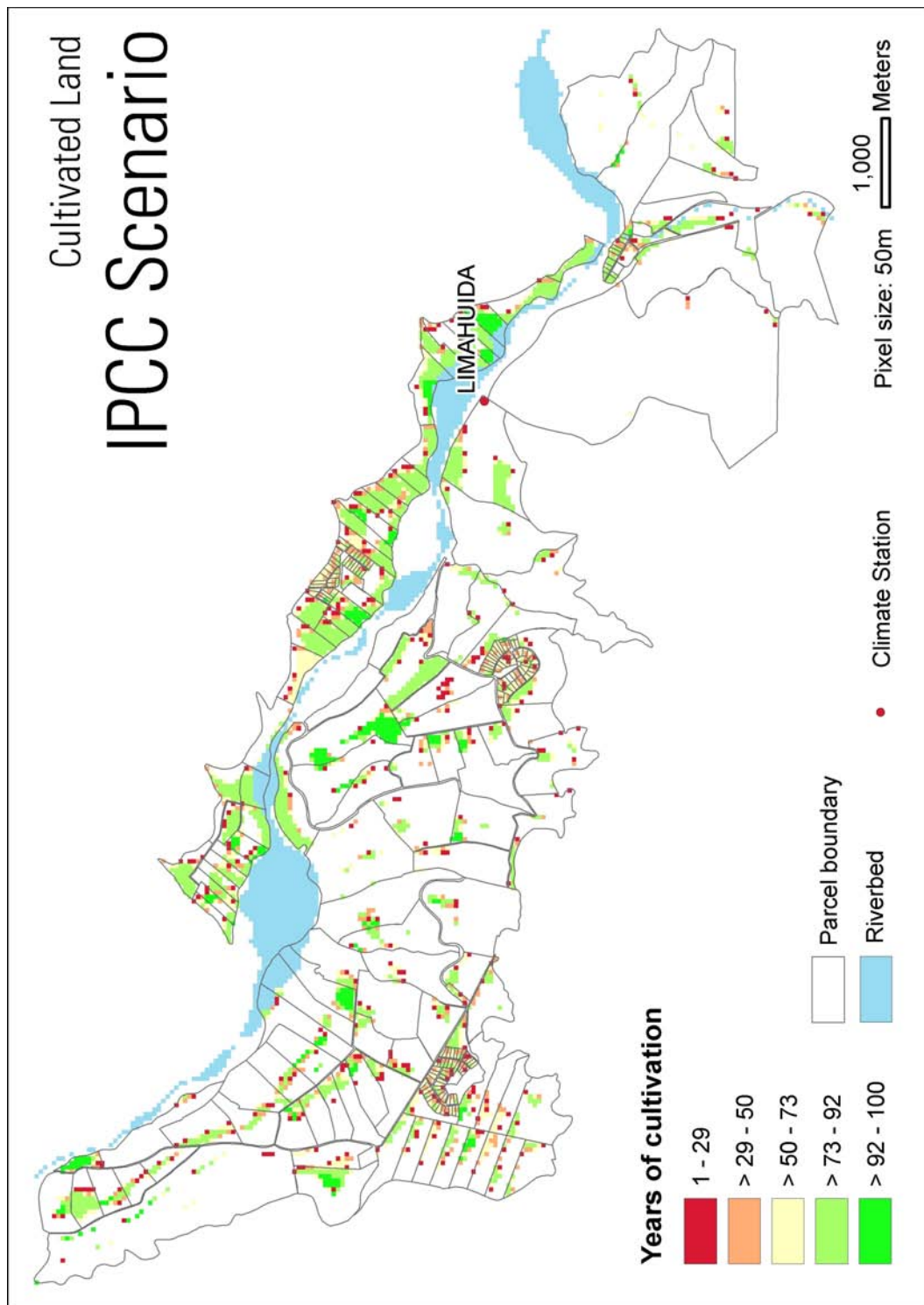


Figure 4-30: Simulation output of the 'Base' and the 'IPCC' scenario.

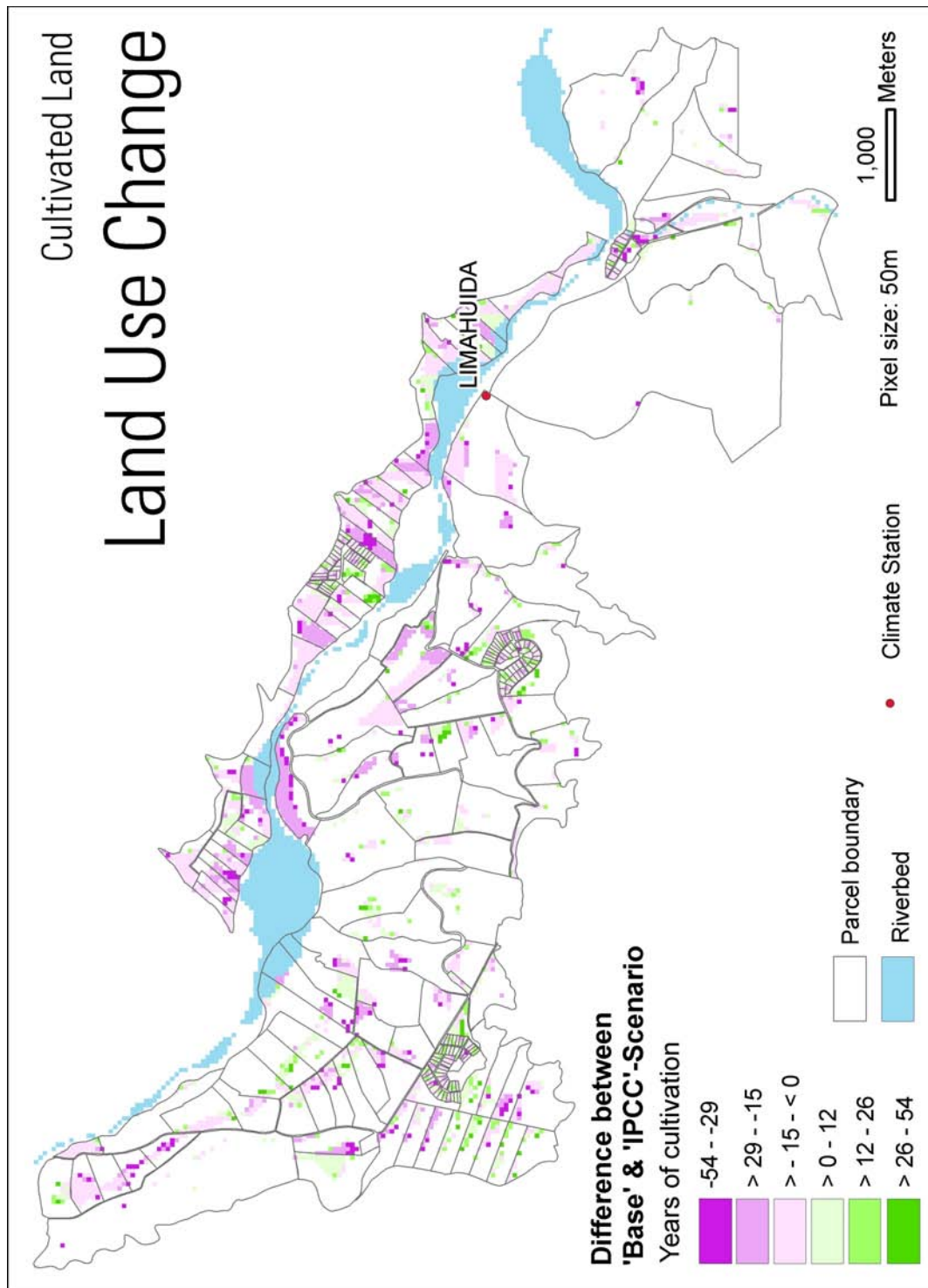


Figure 4-31: Local analysis of time sequence: Calculated difference.

4.6.3 Results, Interpretation and Hypothesis Building

4.6.3.1 Precipitation, Reservoir Level & Cultivated Land,

According to the methodology described in Section 4.5.3 the first 42 years of precipitation were drawn from a series of climate records from the **DGA 2004**. As already shown in Section 4.6.1, a long period of relatively low precipitation between year 6 and 16 led to one of the most severe droughts in the region's history. The simulation model accounted for the low precipitation values with a constant and rapid water level decrease to fewer than 40 percent of the reservoir's capacity (Figure 4-27). This period of water shortage resulted in a migration process of the farmer households between year 15 and 21 and a subsequent decline in agricultural production.

In the following years, between year 21 and 25, the water resources stabilized due to increased rainfall, showing values above the average. Due to the better situation, the migrated farmers returned to their parcels and continued agricultural activity.

According to the sub model of technology adaption, the farmers tried to stabilize their production yield by increased investment in water technology between year 10 and 20. This had the effect of a strong overall water efficiency increase for the region and increased the possible agricultural production level by about 5-8 percent.

The following precipitation records, after year 42, were drawn from a uniform random function, setting 215 as a mean and 120 as standard deviation. In the first ten years, the function produced precipitation values below the average in all year except one. This again caused a strong water shortage which was even higher than that of the drought in 1978. The model simulated a strong decline in the reservoir level, which is more intense than the drought of year 17. Again, a pronounced migration process can be observed, and the agricultural production decreased; that is, about 40 percent in five years. Four years of stagnation on this level followed. Due to the decreased water demand, the water level rose again, and with increased precipitation inflow starting from year 54, the supply situation stabilized and the farmers migrated back into the region.

Even if no climate change is introduced in the simulation, the climate variability causes a very high vulnerability of the system. The given reservoir buffer capacity cannot mitigate the effects of strong climatic anomalies.

The differences between the two scenarios are relatively small, due to the fact that the introduced climate change factor – minus 0.7 percent per year – still did not account for an important precipitation decline. However, it can be noticed that the migration process is more intense: it runs more rapidly and the number of farmers' migration is higher.

Interpreting the drought simulated for the year 2007 to 2019, it can be noted that the recuperation of the system started and finished earlier for the IPCC-Scenario than for the base scenario. This could be due to the fact that the strong migration at the same time decreases the water demand, filling the water reservoirs more rapidly.

During the mentioned drought, the model simulated another 'boost' in water efficiency due to the strategy of many farmers to react to water shortage by investing in water saving technology.

A period of 15 years of relative stability follows. The relatively high precipitation values even produce a significant overflow, which to a certain degree (controlled by the *overflowUse* factor; see 4.5.4.1 p. 46) account for an oscillation of the area of cultivated land between year 65 and 75.

However, then, in the next 25 years, a trend towards decreasing precipitation can be noted. This period starts with two years of only 50 and then 10 millimetres of precipitation which caused the water level drop dramatically. For the base scenario, this still did not have a strong effect on the system, apart from a few farmers migrating out of the system. Nevertheless, for the IPCC scenario, the model simulated negative effects of the increased drought, which are not simulated for the base scenario. First of all, the very low level of year 81 triggered a mechanism of the model, which is built in to prevent the water level from emptying completely; that is by placing a use restriction to the farmers' water rights. This is limiting water usage for the following year in order to let the water level recuperate.

Then, in the following years, the water level could not recuperate due to the significantly lower precipitation values. The model simulates another strong drought situation, with negative effects on migration and agricultural production in the region. Although the system could somehow recuperate between 87 and a 95, the water level dropped again.

The third drought situation simulated by the model permits a formulation of the hypothesis that ongoing climate change is responsible for more pronounced droughts, which in return can lead to a series of negative effects like migration and production loss, which would not have happened under 'normal' circumstances; that is without climate change.

4.6.3.2 Local Spatial Analysis

Two different criterion maps were evaluated by each farmer through weighted overlay techniques (see Chapter 3: Spatial Decision Making). The slope factor and the 'distance to water' factor were the two criteria for the spatial part of the decision model. The results of the Agent-Based evaluation of their parcel are shown in Figure 4-13, p. 58. This snapshot was taken after the first simulation step. The colour indicates the suitability for cultivation of a cell according to the individual preference set of the farmer. Suitability ranges from zero, with reddish colours, to 255, with green colours indicating full suitability.

The map shows clearly that the suitability decreases with increasing distance to water, as well as with increasing slope. As each farmer could have had individual preferences assigned, there are notable discontinuities in the suitability distribution. For example, in the north-western part of the study area, a significant difference between adjacent parcels can be noticed, which is neither a result of slope nor distance, but of different preferences of the farmers. Furthermore, as a result of the time dimension introduced, the suitability can change from year to year as a result of intrinsic adaptation of the farmers (see Section 2.5.3: Intrinsic Adaptation).

Snapshots of different suitability maps are shown in Figure 4-13 (25 year interval). The maps show how different preference sets of individuals can have a spatial impact on land use and on land use change. In this case, the spatial distribution was modified by the fact that a farmer had a different technology level, and as a result would preferably cultivate on locations that meet the requirements of the technology used. For example, a farmer with a high technology level who uses a water distribution system based on water pumps is less dependent on the slope factor than a farmer, who applies a gravity approach for the same task.

The values in Figure 4-28 and Figure 4-29 represent the number of years a cell was cultivated under the given simulation parameters (Figure 4-25 and Figure 4-26) in the 100 years sequence. Corresponding with the outcome of the weighted overlay operation and the resulting suitability map, the distribution of agricultural

activity and the number of years a cell was cultivated, is displayed. Green colours represent cells, which were cultivated more frequently than the mean frequency (mean value: 73). For example, a value of 80 signifies that the cell was in use in 80 percent of the years.

The high mean value indicates that the variation is relatively low. However compared to the IPCC-Scenario, this value drops to 68. This was expected due to decreasing precipitation and migration of farmers.

Cells with a higher value than the mean frequency can be interpreted as agricultural 'core' areas. These cells might be more sustainable than cells below the mean frequency, because they were constantly cultivated, despite the fact that the region suffered from water shortage in several years. Cells with a lower value than the mean frequency can be cultivated only in times when enough water resources permit a continued agricultural activity.

Figure 4-31 shows the difference between the two scenarios. Only cells on which a change was noticed are shown on the map; cells values of zero – these are cells which had the same amount of years cultivated in both scenarios – are excluded.

The first thing to be mentioned is that the total sum of cultivated land dropped from 55429 hectares for the base scenario to 50736 hectares for the IPCC Scenario, which corresponds to a decrease of 9.47 percent. This is manifested by a predominance of purple colours on the map.

Secondly, the range of values is from -54 to +54. This was surprising, as this indicates that there is not a decrease applied to every cell only, but this shows that there are also cells in which the number of years under agricultural production *increased*. A possible explanation is that the intrinsic adaptation of the decision making preferences produces a slight spatial shift from plain slopes to steeper slopes and from locations near the river bed to locations further away. This mainly applies to farmers who migrate out of the system and then back again. These farmers adjusted their decision preference in time. However this had an effect only on those cells, which were added or removed from the existing ones. If a farmer moves out of the system, he completely removes all cells and then replants his parcel completely new, based on the changed preference set if he remigrates. Therefore, the new locations are based on the adjusted preference set by the farmer. This spatial structure can be identified clearly in some parcels where predominantly purple cells indicate a decrease, and a few green cells indicate an increase.

Nevertheless, some of the parcels show and pronounce increase, which cannot be explained by the former hypothesis. Here, a second process takes place: as can be seen in Figure 4-27, between year 55 and 60 *more* farmers cultivated a parcel in the IPCC scenario than in the base scenario. As a result of this, some of the parcels show a positive anomaly. This possibly adds to the former mentioned effect of spatial shift. However, a third explanation might be applicable here: The two simulation runs produce different migrations patters. This would indicate that the farmers' willingness to migrate is not linearly related to the water supply situation. In other words, it might be the case that a farmer migrates if the water level drops to an intermediate level, but stays if the water supply drops dramatically. This is somehow not logical, however possible in some situations, like if a severe drought causes some kind of fatalistic attitude in regard to the future, resulting in lethargic inactivity.

Weather or not this is an artefact of the model, or an emergent property of the system should be discussed in detail. Hence it can be said, that further research on this topic appears to be necessary.

4.7 Model Validation

Calibration was part of the models' coding and testing process. Calibration is similar to validation; however it refers to fitting the model to data *before* running the model, while validation involves comparing model outcomes to data. Validation is therefore concerned about how well a model characterizes the system it is meant to represent (Gardner & Urban 1991).

The spatial decision making component was validated in order to test the agents' decisions to real world data. The strategy was to compare a suitability map to the real world land use. The mentioned suitability map (see Figure 4-28) is a product of individual agent decisions, which is given after the first iteration of the simulation. After the first iteration, the agents evaluated their parcels according to the preference set given to them. The two factors, which the agents evaluated, were 'slope' and 'distance to river'. A constraint map masked the decision space to areas outside the area of influence of the river. The result is a cost surface. This cost surface reflects the suitability for agriculture. Based on this suitability raster, the agents decide where to cultivate.

The Relative Operating Characteristic (ROC) model was used to validate the suitability map to real world agricultural land use in the study area. Eastman 2003 explains:

“The ROC assesses the validity of a model that predicts the occurrence of a class by comparing a quantitative image depicting the likelihood of that class occurring (the input image) and a Boolean image showing where that class actually exists (i.e., the reference image). A ROC value of 1 indicates that there is perfect spatial agreement between the class map and the suitability map. A ROC value of 0.5 would be expected if there were no spatial agreement (e.g., if the input image values were assigned to random locations)”.

The input image used is the exported cost map, whereas the reference image is a land use map which was created by the CEAZA (Centre for Advanced Studies in Arid Regions) through manual interpretation of areal photos, with a scale of approximately 1: 25000 for the forest agency of Chile (CONAF – Corporación Nacional Forestal).

The first calculation was carried out with global decision making, which means that every agent has the same decision making preference. The result of a ROC-value of 0,810 indicates an acceptable spatial agreement with the reference image.

In the second calculation, each farmer was assigned an individual spatial preference, which was given out depending on the type of farmer (commercial or subsistence). It was assumed that the commercial farmers' decision preference primarily depends on the distance to water, because he usually has the necessary irrigation infrastructure (pumps, sprinkler systems) to overcome slope constraints. In the case of the subsistence type farmer, the slope criterion is more important, because he is usually practicing traditional type irrigation methods like flushing etc. As these methods are based on gravity, the slope criterion is more important for this type of farmer.

The result of this calculation is satisfactory as well; it even shows a value that is slightly higher: 0,812.

4.8 Model Verification

After the calibration and the first model runs, the author passed the model outcomes to the experts of the regional ministry of agriculture. They were asked to verify the strong decline in agricultural production in the period between time step 16 and 27, which corresponds to the year 1977 and 1988. The response was quite surprising, as within this time, the region was affected by two severe droughts (CRIA 2005).

The negative amount of rainfall was assumed to have been caused by the El-Nino Southern Oscillation (ENSO). In the year 1977 the drought started - an assumed 'La Niña' event - and affected the region severely for about 4 years. Then in 1983 an increased rainfall, which is believed to be an effect of an 'El Nino' event, helped the region to recuperate. Then again in the year 1984 to 1986 the region suffered from another drought, and then again, in 1987, the 'El Nino' brought precipitation to the region.

However, analysing the precipitation data of the Choapa Valley, it is difficult to establish a direct relation between precipitation data and the droughts, as between the years 1977 and 1988 the precipitation was relatively high. Only after the reservoir level decreased to a level which could not supply enough water for agriculture,

the migration process and agriculture downfall commenced. A possible explanation for this would be a time delay causing this low precipitation to take effect about 4 to 6 years later. The time delay might have been caused by a combination of two interconnected delays of the system. Firstly, water resources accumulated as snow cap in the Andean mountains as well as groundwater inflow can maintain supply another two to three years. Secondly, the reservoirs of the region account for another delay of about 2-3 years.

5 Conclusion and Outlook

Research Objectives

The main objective of this work was to develop a spatially disaggregated modelling framework to explore the external and internal factors that influence the spatial dynamics of irrigation agriculture in the face of the high short-term climate variability and the long-term climate change in the Choapa Valley in Chile.

This goal was met, as the object-oriented approach is flexible enough to be adjusted to further requirements and to more complex functioning. The model could act as a computer laboratory to explore the dynamics from different perspectives and at various levels. The main parameters that determine the spatial dynamics of irrigation agriculture were identified – the prototype parameters like amount and variability of precipitation, precipitation and climate change, migration, reservoirs and water efficiency are accessible in the graphical user interface of the simulation, and can be altered in order to explore the effects. However, at the current stage, the model is a ‘prototype’, and is therefore at its initial design stage. Yet, it served as a learning tool to explore and understand the system in question, and thus can be used by researchers.

The main parameters mentioned have been calibrated, the model’s behaviour meets the expectations, and the model produces reasonable results. Although there were no breaking emergent properties identified, there have been several eye-opening effects during simulation runs. For example, the model could replicate a drought situation with negative consequences on the agricultural system (migration, production loss) within a range of a few years.

Based on the comparison of two different scenarios for a one hundred year period, the model simulated that the system stability is affected in a dramatically way, first by intensifying the problems caused by natural climate variability and second by producing an agricultural crisis, which would not have happened under ‘natural’ system dynamics.

For this purpose, the model should be passed on to a team of local experts and stakeholders to explore and test the model. A participatory modelling process

would definitely increase the validity of the simulation, and would make the model more acceptable for the stakeholders. The model could then provide a basis for discussion about the implementation of adaptation and mitigation strategies that help to cope with the expected land use change in the following decades ahead.

Another objective was to explore and evaluate the Agent-Based Modelling approach in the face of spatial analysis and coupling to GI-Systems. It was proved that the combination of Open Source software like RePast and Software development kits like ECLIPSE combined with GIS software can be an effective and easy-to-handle framework. The loose coupling of an Agent-Based Model and GIS can be accomplished in a relatively easy way, providing data exchange through ASCII raster datasets in the shape of textfiles. A tighter integration increases development cost significantly, and should be compared to expected benefits, especially in situations where sub-models like climatological models should be included.

Regarding spatial capabilities, the model shows that basic spatial analysis is possible within the Agent-Based Model. In special cases, this should be the preferred method, because there is full control over the applied algorithms and formula, which is often not the case with out-of-the-box Geographic Information Systems.

Validation, Verification and Model Communication

Although some model validation and verification was carried out, a proper sensitivity analysis is necessary in order to identify parameters which account for bigger changes in the simulation output if a parameter is modified only little. Furthermore, the sensitivity analysis could identify parameters, which do not account for the explanation of the output.

It is difficult to communicate the model structure, functioning and output of Agent-Based Models. Some of the models are so complex, “that [they] are as hard to understand as the real world, and therefore of little use” (Grimm & Railsbach 2005, p. 17). Although the model is relatively simple, the model structure, functioning and rules were described as detailed as possible.

Further Development

At the current stage the model cannot be used as an empirical prediction model. The full potential of the simulation will only be unfolded if the model is updated

and adjusted with stakeholder participation. There are two possible developments. One development could be towards of a more complex, empirical model which could be used to make predictions more definite. The probability that the simulated drought beginning in the year 2007 and the negative effects will happen is rather small. However, the existing model structure provides a good basis for a further development of the model. Empirical data about farmer households can easily be integrated when data of the next agricultural census will be available. Existing GIS data can be integrated into the model as information layers. Like this, more decision making factors add to the existing and could provide a more sophisticated decision making engine. A possible extension of the spatial decision making capabilities could be 'risk-aware' agents applying more complex aggregation rules like 'Ordered Weighted Averaging' (Malczewski 1999, Mysiak 2004).

The concept of spatially enabled agents should be extended. In further versions of the models, agents will be 'aware' of their neighbours who communicate and interact with them. To account for these social agents, social scientists must be included in the modelling in order to provide a stable psychological and sociological basis for decision making and behaviour of the agents.

Hydrologists of the relevant institutions are inevitably needed and invited to validate the model and to improve the hydrological model. These kinds of models are under development by CAZALAC 2005, and could for example introduce a finer time scale. This would make it possible to account for the very inhomogeneous distribution of rainfall in the region. Furthermore, information about groundwater quantity and usage does not play a role in the model so far, but could cause interesting behaviour.

CAZALAC 2005 could also provide the model with a more differentiated view to the topic of efficiency. For example, there is an 'institutional efficiency' ("efficiencia institucional") (CAZALAC 2005) related to water efficiency, which could be integrated, because institutions as well could be modelled as agents and incorporated as a higher level concept of "aggregated behaviour" (Parker et al. 2001).

The possible development is to keep the model relatively simple, but extend the model in order to serve as a tool for group decision making and for role-playing games (Aquino et al. 2003, Barreenteau et al. 2001 and Barreenteau et al. 2003, Vennix 1999). This could provide a tool for strategic assessment and for scenario analysis for the decision makers. For example, a decision maker or a group could develop different development scenarios for the region and test and discuss them in a participatory setup in order to facilitate a participative and democratic deci-

sion process. **Parker et al. 2001**, p. 94 argue that Agent-Based Models can promote and support discussions among stakeholders by “(c)ollectively creating an artificial world [...] within the computer” [which] “helps stakeholders become aware of the specific views of other land users and might lead to improved decision making”. The IDAGON management flight simulator is a good example for this kind of simulation (**Ford 1999**).

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7 Annex

7.1 CD-Rom

The hardcopy of this work contains the following resources on CD-Rom:

- the source code of the Choapa Model
- the model's executable file (JAR-File)
- a copy of Repast 3.1 and Java for Windows
- raster and vector geodata used in this work

7.2 Model Installation

In order to run the Choapa Model, the user has to consider the following steps:

1. A recent version of the Java 2 Runtime Environment (v 1.4.2_09 or higher) must be installed. The download is about 15 Megabytes. An installation of the Software development Kit is not necessary. A recent version of Java for Windows is included on CD-Rom. If you want to download Java directly from the distributor, he should go there:

<http://java.com/en/download/index.jsp>

2. Once Java is installed, the RePast3 software has to be installed with the standard settings. A copy of the Repast Simulation Kit installer version 3.1 is included on CD-Rom. For a direct download, go to:

<http://repast.sourceforge.net/download.html>

The following explanations are extracted from the repast documentation. For a detailed description, for example if the simulation should run on a UNIX station, refer to <http://repast.sourceforge.net/how-to/simstart.html>.

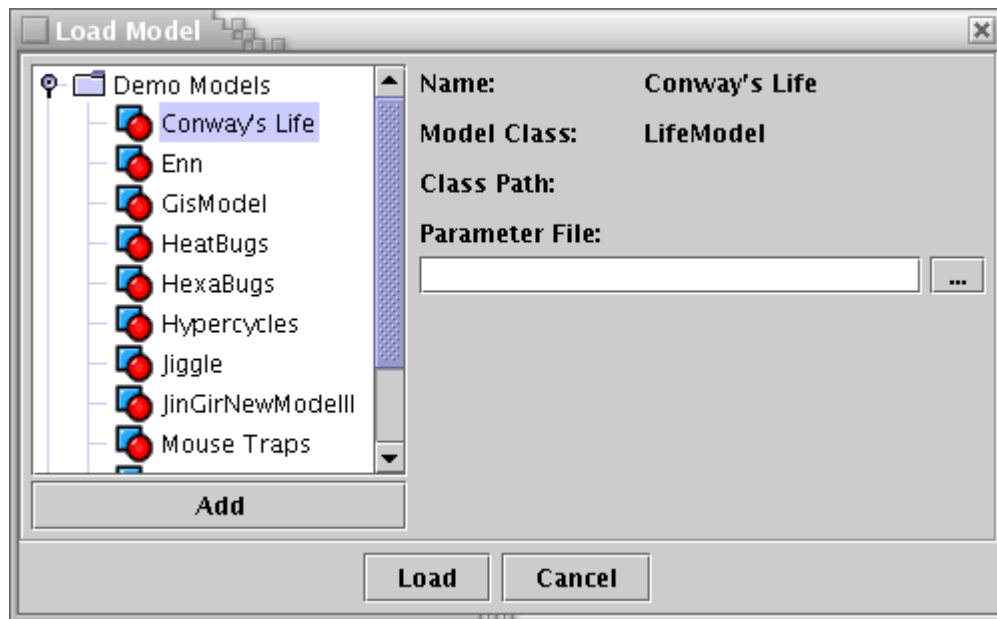
In order to run the Choapa Model, one first has to start Repast. This can be done in a variety of ways. On a Windows system, one should be able to right-click on the file repast.jar file in the repast\lib directory. Alternatively, the installation process may have created a link on the start menu. However, Repast can always be started from the command line in whatever OS (Windows, UNIX, Linux, or MacOS X) that you use. For example, the following

```
java -jar c:\repast\lib\repast.jar
```

will start Repast on windows assuming Repast is installed in c:\. When Repast starts the graphical user interface will show.



A click on the folder button will display a dialogue for loading a simulation model into Repast.



The tree on the left of the dialog contains all the demonstration models that are distributed with Repast together with any simulation models that are contained in the `repast\models` directory. To load a model into Repast, one has to click on the appropriate node in the tree and then on the load button.

To add new models to the tree so that one may load them, one has to click on the add button. One can then use the file dialog to find the `choapa.jar` file provided on CD-Rom. Once the model has been loaded, it can be run via the toolbar. Switch to the 'Parameters' Tab in the ChoapaModel settings window in order to examine and change the parameter settings.

When the model starts, 5 windows will open containing the display surface and the output graphs. It might be necessary to resize certain windows and to arrange them to ensure a clear view of all windows.

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Signed: _____

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